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The Star Splitters

The High Energy Astronomy Observatories

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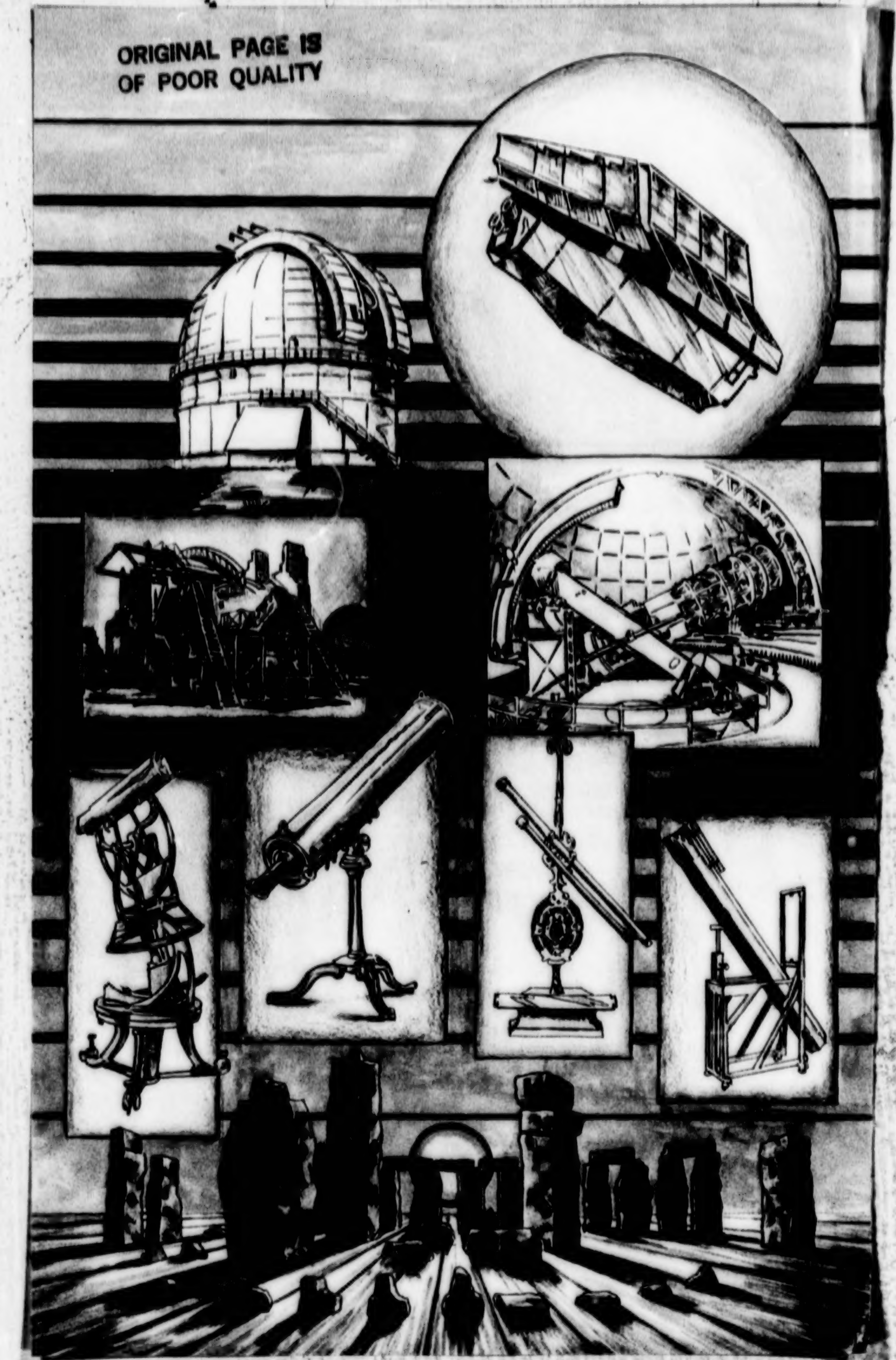

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The Star Splitters

The High Energy Astronomy Observatories

Wallace H. Tucker

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FOREWORD

Wallace H. Tucker's *The Star Splitters* is the story of a space science project. It traces, literally from before the word "go," the many elements of a major and highly successful space program: NASA's High Energy Astronomy Observatory (HEAO) Program. Astronomers began to dream about the research they would ultimately do with HEAO back in the mid-sixties. Today, 20 years later, some of those same astronomers are still writing papers on the results of that research. You will learn how a science project is conceived, funded, and managed, and you will experience with the HEAO team the emotional ups and downs and the frustrations and rewards that go with participation in such a venture. Dr. Tucker, a lucid writer as well as a distinguished scientist, brings alive the human drama along with the significance of the discoveries made with HEAO.

You will learn much about our universe from this book—from the creative violence that spawns new galaxies, planets, and ultimately you and me, to the nature of the galaxies' missing mass. The scientific discoveries on the three HEAOs greatly exceeded the anticipation of the astronomers. While the team of scientists, instrument and spacecraft makers, and NASA engineers and managers were confident of success prior to the launches, there was no way they could predict what the delicately aligned telescopes would detect as they probed across the sky.

HEAO was an outstanding technical as well as scientific accomplishment. Once through its initial growing pains it was brought in on schedule and within cost. This was a particularly significant achievement because a major effort to reduce costs was made in the HEAO Program. The cost per pound of scientific instrumentation for the HEAO instruments was 40 percent below the NASA average up to that time. HEAO demonstrated a new concept of building, testing, and flying one set of "protoflight" hardware, where previously NASA had built structural models, thermal models, prototype systems for integration, and finally the actual flight hardware. For HEAO only one set of hardware was built which was then assembled, tested, and flown. The integrity of this approach was reflected in the excellent orbital performance.

The magnificent scientific and technical accomplishments of HEAO are a tribute to the quality and outstanding teamwork of the scientists, engineers, and managers at NASA Headquarters, the Marshall Space Flight Center, TRW, and the many university and government laboratories involved in HEAO.

This book, then, is dedicated to all the men and women in government, university, and industry who contributed to the success of HEAO.

It's good reading!

John E. Naugle
NASA Associate Administrator, 1975–1977

ACKNOWLEDGMENTS

One of the most enjoyable parts of writing this book has been the opportunity to meet with some of the people involved in the HEAO program and to talk with them about their participation in HEAO. It gives me pleasure to acknowledge discussions with Gerry Austin, Elihu A. Boldt, Stuart Bowyer, Hale Bradt, E.T. Byram, Claude Canizares, George Clark, Talbot Chubb, Roger Doxsey, Robert Farnsworth, Herbert Friedman, Riccardo Giacconi, Paul Gorenstein, Art Gneiser, Herbert Gursky, Richard E. Halpern, F.R. Harnden, Jr., J. Patrick Henry, Stephen Holt, Martin H. Israel, Allan S. Jacobson, Ray Jorgensen, Lydie Koch-Miramond, Walter H.G. Lewin, James Matteson, Frank B. McDonald, Steve Murray, Marshall Novick, Albert G. Opp, Tom Parnell, B. Peters, I. Rasmussen, Tom Recio, Gunther Riegler, Ethan Schreier, Dan Schwartz, Fred Seward, Fred A. Speer, Harvey Tananbaum, and Kent Wood. Carroll C. Dailey and Wendell Johnson made helpful comments on the manuscript, as did William W. Pomeroy, who also provided much appreciated advice and support. I also wish to thank all the members of the HEAO team, many of whose contributions to the project were not mentioned specifically; nevertheless, they were vital to the success of the project. Finally, I wish to thank my wife, Karen. Her support, encouragement, and advice throughout the course of this work have been invaluable.

October 1983 W.H.T.

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CONTENTS

Foreword v

Acknowledgments vii

PART ONE: Preview of the Cosmos 1
1. Pointing Our Thoughts 3
2. The High Energy Universe 5

PART TWO: The Star Splitters 11
3. The Road to HEAO 13
4. On the Road Again 23
5. Mission Planning 29
6. The Star Splitters 37
7. New Perspectives in Astronomy 79

PART THREE: The High Energy Universe 83
8. Creative Violence 85
9. Explosion of a Star and a Myth 89
10. Cosmic Ray Surprise 95
11. Superbubbles 99
12. Stellar Coronas 103
13. Collapsed Stars 111
14. Pulsars 113
15. Tides in the Affairs of Neutron Stars 119
16. Degenerate Dwarfs 125
17. Black Holes 129
18. The Realm of the Galaxies 133
19. X-Ray Images of the Galaxies 137
20. The Maw of the Abyss 143
21. Stripped Spirals and Cosmic Cannibals 151
22. The Mystery of the Missing Mass 159
23. Cosmic Fire 165

Additional Reading 169

HEAO Management Teams 171

Additional Photo Credit 181

About the Author 182

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Part One

PREVIEW OF THE COSMOS

So Brad McLaughlin mingled reckless talk

Of heavenly stars with hugger-mugger farming

Till having failed at hugger-mugger farming

He burned his house down for the fire insurance

And spent the proceeds on a telescope

To satisfy a life-long curiosity

About our place among the infinities.

Robert Frost, *The Star-Splitter*

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1
POINTING OUR THOUGHTS

This book is dedicated to people like Brad McLaughlin. Some would even say that it is *about* people like him, people who have literally burnt the farm down with an expensive space program in order to satisfy a curiosity about our place among the infinities. Although it is true that the multibillion dollar price tag for the space program could have bought a nice farm, even in California, the view that the space program has been a waste is myopic.

It neglects the innumerable spin-offs that have repaid the investment in space technology many times over. Even such esoteric instruments as high energy telescopes have played a role in the development of useful technology: X-ray detectors used to screen luggage at airports, computerized axial tomography (CAT) scanners used in medical examinations, and nondestructive testing whereby turbines of airplane engines can be examined for cracks.

Throughout history, astronomy, the queen of the sciences, though she has had her head in the stars, has always had her feet firmly planted on Earth. From the ancient traders and explorers who used the stars to guide them across unknown waters to the modern entrepreneurs who rely on satellite communication and space age computers, from farmers who planted their crops by the rising of certain stars to agronomers who gather information about crops and weather from satellites, the practical by-products of astronomy have been many and varied.

Astronomy is a science that stretches. The urge to know, to see even deeper into the ocean of space, stretches our machines to the limit and spurs us on to the development of better, more sensitive, and more sophisticated technology that is inevitably useful on Earth.

It stretches our imagination, too, this reaching out across light years to touch a star, this wondering about how it all began and where it is all going. Ultimately, this has to be the true value of astronomy, this effect on the human mind. As Mortimer Adler said, "A mind, once stretched, never returns to its original dimensions."

Robert Frost knew about this aspect of astronomy:

Bradford and I had out the telescope
We spread our two legs as we spread its three.
Pointing our thoughts the way we pointed it
And standing at our leisure till the day broke
Said some of the best things we ever said.

This book is about one of the youngest and most vigorous branches of astronomy, high energy astronomy, and the flights of three High Energy Astronomy Observatories. It is also about the flight of the human spirit, about men and women and their marvelous machines, and what they have learned about our place among the infinities.

2

THE HIGH ENERGY UNIVERSE

Astronomy has traditionally played a major role in the advance of knowledge in the physical sciences. From Newton through Einstein up to the present, the contributions of astronomy to the development of such fields as mechanics, gravitation, relativity, atomic physics, nuclear physics, and elementary particle physics have been important and at times crucial. In many cases astronomical observations provide the only means for studying phenomena occurring in matter under the most extreme conditions of temperature and density. In addition, every so often astronomical discoveries are made that are so surprising and enigmatic that they serve as a stimulus for the further development of a particular branch of physics and sometimes lead to completely new theories. In the past two decades a spectacular series of discoveries of this type has occurred, primarily as a result of the development of techniques for exploring regions of the electromagnetic spectrum outside the "optical window."

Light, or optical radiation, is part of a large family of radiation called electromagnetic radiation. This radiation is usually produced when electrons, the tiny charges on the outer parts of atoms, undergo rapid changes in their state of motion. These rapid changes or accelerations, which can be thought of as vibrations, produce bundles of energy called photons that move away from the electrons at the speed of light. (All electromagnetic radiations move at the same speed in a vacuum.) In general, the more rapid the vibration or acceleration, the more energetic the photon. For example, to produce an X-ray photon requires a vibration several hundred to a thousand times more rapid than for an optical photon, which in turn requires a vibration millions of times more rapid than necessary for the production of radio photons.

Streams of photons behave in many ways like the water waves you can set into motion by moving your hand rapidly back and forth in a tub of water. Like water waves, electromagnetic waves have wavelengths and frequencies that depend on how rapidly the electrons producing the waves vibrate. A high frequency wave is composed of high energy photons, a low frequency wave of low energy photons.

Electromagnetic waves come in all wavelengths, but our eyes are sensitive to only a very small portion of the total range or spectrum. To the long wavelength (low frequency) side of the optical portion of the spectrum we encounter the infrared, microwave, and radio radiations, in order of increasing wavelength (decreasing frequency). To the short wavelength side lie

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Type of radiation
Wavelengths
Frequencies (Hz)
Energies (electron volts)

The electromagnetic spectrum. The spectrum of electromagnetic radiation extends over all possible wavelengths and frequencies, from the long wavelength (low frequency) radio waves to the short wavelength (high frequency) gamma rays. Visible light has intermediate wavelengths and frequencies.

the ultraviolet, X, and gamma radiations. It is certainly no accident that our eyes are sensitive only to optical radiation. For one thing, the strongest source of electromagnetic radiation in our cosmic neighborhood, the Sun, emits most of its radiation in the optical range. Furthermore, water vapor, dust, ozone, and other molecules in the upper atmosphere absorb most of the radiation at other frequencies.

There is an opening in the atmospheric screen at radio frequencies, and it is there that the exploration of the invisible universe began in earnest in the early 1950s. Radio astronomers soon discovered, much to everyone's surprise, that stellar explosions, or supernovae, release tremendous amounts of energy in the form of high energy particles. Then followed the discovery of radio galaxies and quasars, leading to the conclusion that explosive phenomena are taking place on a very large scale in galaxies as a whole and that high energy processes play a large and quite possibly a decisive role in the structure and evolution of our universe.

There had been a hint of this earlier, in the form of the cosmic ray particles that constantly bombard the top of Earth's atmosphere. Cosmic rays consist of bare hydrogen nuclei, or protons, together with a few heavier nuclei, also stripped of their electrons. They are distinguished from other particles that encounter Earth (in the solar wind, for example) by their high energy and by their arrival at Earth from all directions, which show that they cannot come from the Sun. Measurement of the numbers of cosmic rays striking Earth per second and of their energy indicate that high energy particles constitute a major component of the energetics of the galaxy.

Although it was realized in the 1930s that charged particles were coming into our atmosphere from space, it was not until the late 1950s that large high altitude balloons allowed experimenters to place their instruments above most of the absorbing atmosphere and study the basic properties of cosmic rays. Gamma rays and high energy X-rays (the distinction between the two is no more than a matter of terminology) can also be observed from high altitude balloons, but the more plentiful low energy X-rays are absorbed a hundred miles above the surface of Earth. It was not until the coming of the space age that experiments in the early sixties aboard rockets and satellites gave us our first glimpse of the X-ray universe.

The sky was found to be aglow with X-radiation, equally intense from all directions. The origin of this diffuse X-ray background is still a puzzle, but its uniformity over the sky implies that it was created at least ten billion years ago, about the time that galaxies were formed.

The early X-ray experiments also detected concentrated emission from several objects familiar to astronomers, such as the remnants of exploded stars and explosive galaxies. In addition, a new class of objects, X-ray stars, was discovered. These objects radiate almost all their energy in the X-ray band of the spectrum and have a total power output comparable to that of ten thousand suns. The nature of X-ray stars was a subject of lively debate and controversy among astronomers until a dramatic breakthrough was achieved in 1971. Scientists working with data from NASA's first X-ray satellite, UHURU, conclusively established that some and perhaps all X-ray stars are members of double star systems in which X-rays are generated by the infall of matter from a giant star onto a collapsed companion star. In many cases the collapsed star is apparently a neutron star. A neutron star is thought to be the collapsed remnant of an exploded star, a bizarre world of superstrong magnetic fields, and matter crushed to densities trillions of times greater than ordinary matter. (A grain of neutron star material 1/10 of an inch in diameter would weigh as much as an aircraft carrier.) Gamma ray observations indicate that neutron stars sometimes undergo cataclysmic

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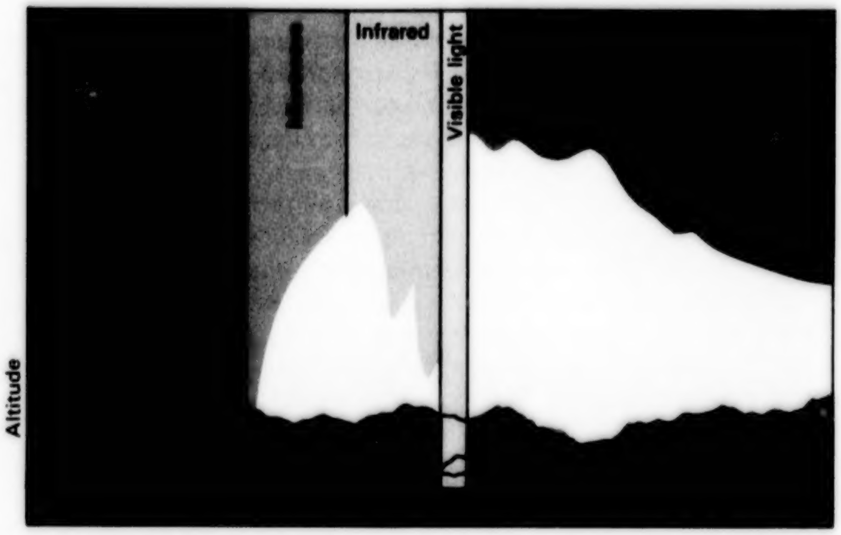
star quakes that release as much energy in a few seconds as the Sun releases in several years.

In some instances, the collapsed X-ray star is too massive to be a neutron star. In these cases it is believed that the stellar core has imploded, or collapsed in on itself, forming a black hole in space, a region from which nothing can escape. Matter pulled off the companion star by the gravitational field of the black hole is compressed and heated as it swirls around the black hole, giving off a flash of X-rays before falling in.

As a result of these and other discoveries, high energy astronomy, that is, the study of X and gamma radiation and cosmic ray particles, has flourished as have few other fields in the history of astronomy. Physicists and astronomers have come to recognize it as an essential tool for investigating the laws of the universe. High energy observations give us access to regions of space that would be difficult if not impossible to study by traditional means. We can examine the surfaces of neutron stars, peer close to the event horizon of black holes, study the energy and chemical composition of particles produced in stellar explosions, probe the violent nuclei of galaxies to greater depths than ever before, trace the evolution of groups and clusters of galaxies by studying the hot gas they produce, and set limits on the size, structure, and evolution of the universe as a whole.

The sophistication of the tools of high energy astronomy has increased dramatically over the past two decades, culminating in the High Energy Astronomy Observatory (HEAO) program, which put three satellites into



Earth's atmosphere absorbs radiation of most wavelengths at varying heights above the ground. Visible light and some radio and microwave radiation reach ground level, but other wavelengths are blocked at high altitudes. Orbiting detectors sensitive to these radiations have recently opened up new windows of the universe.

orbit, each carrying over three thousand pounds of experiments. This program has transformed high energy astronomy from an interesting tributary or side branch to one of the main channels of astronomical research. In addition to providing information on phenomena that could be only poorly studied in the past, virtually every known astronomical object has been found to emit measurable quantities of high energy radiation. The HEAO experiments have made it abundantly clear that if we want to understand an astronomical object, we must look at its radiation at all energies, not just in the narrow optical band.

The HEAO program, then, has not only changed our knowledge of the astronomical universe, it has changed the way that astronomy is done. It has been, in the words of Herbert Gursky of the U.S. Naval Research Laboratory, "a landmark in NASA's space science program." Of course, programs of that magnitude don't just happen. They require vision, planning, politicking, compromise, sacrifice, and years of hard work.

Part Two

THE STAR SPLITTERS

The telescope was christened the Star-Splitter

Because it didn't do a thing but split

A star in two or three the way you split

A globule of quicksilver in your hand

With one stroke of your finger in the middle.

It's a star splitter if there ever was one

And ought to do some good if splitting stars

'Sa thing to be compared with splitting wood.

Robert Frost, *The Star-Splitter*

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THE ROAD TO HEAO

The traditional image of an astronomer is a shy, pipe-smoking man, patient to a fault, who would rather spend his nights on a lonely mountaintop gazing at the stars than at home in bed. This caricature never did apply to more than a few astronomers, and it applies to fewer still in space astronomy. Successful space astronomers are at the same time scientists, managers, and entrepreneurs. They must understand nuclear physics as well as Einstein's theories and be familiar with the working of telescopes that are as complicated as a jet aircraft. They must direct the work of dozens of scientists, engineers, and technicians, and they must sell their ideas to funding agencies. They must be ready to wheel and deal if necessary to get space for their project on a satellite, and they must always be ingenious, for there is never enough time or money to do everything that should be done. Above all, they must be dreamers, for only a dreamer would undertake a project that will take a decade or more to come to fruition.

The idea of the High Energy Astrophysical Observatories, or HEAOs, was conceived in the 1960s. This decade, noted for its political turmoil, was also a turning point in the history of astronomy. It was one of those golden, exhilarating ages when discovery followed upon discovery: quasars, X-ray stars, gamma ray sources, pulsars, the cosmic microwave background radiation, all indicating the importance of high energy processes in the universe. It was also the time when the nation made and carried out a commitment to put a man on the Moon. Both these developments were crucial to the ultimate success of the HEAO program. On the one hand, the discoveries gave tremendous scientific impetus to high energy astronomy; on the other hand, the rapid development of the space program assured the technical capability necessary to put large space experiments in orbit.

In the early 1960s three different groups were moving along independent paths toward what would eventually become the HEAO program. There was the group at the Naval Research Laboratory (NRL). This group, under the leadership of Herbert Friedman, had been the first to detect X-ray emission from a cosmic source, the Sun. Using rocket-borne detectors, they had been studying the solar X-ray emission for over a decade and had made unsuccessful attempts to detect X-rays from sources outside the solar system. What was needed, Friedman felt, were larger detectors with better efficiency and larger area.

Of course, no one knew for sure just how efficient the detectors would have to be, since the properties of the X-ray sky beyond the solar system

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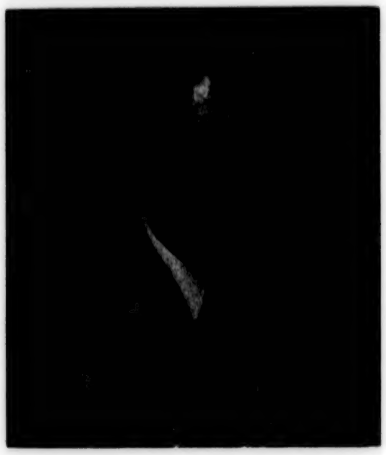
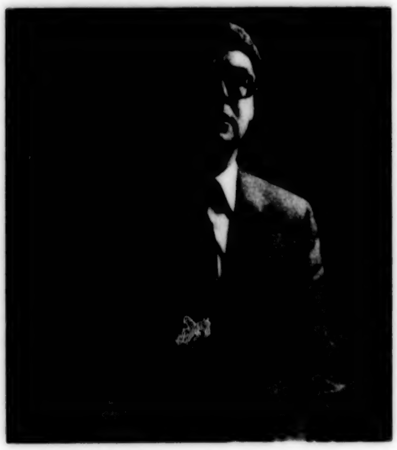


Herbert Friedman

were a complete mystery. If all the stars were about the same strength as the Sun, then detectors thousands of times more efficient would be needed. This would mean detectors with thousands of times more area than those currently in use, or an X-ray telescope which could focus many X-ray photons into a small area. The idea of a focusing X-ray telescope captured the imagination of two physicists in Cambridge, Massachusetts, Bruno Rossi of the Massachusetts Institute of Technology (MIT) and Riccardo Giacconi of American Science and Engineering (AS&E). In parallel with a program to detect cosmic X-rays by more conventional techniques, they began their active advocacy of focusing X-ray telescopes.

In June 1962, the AS&E-MIT group flew a rocket experiment that succeeded in detecting the first X-ray source outside the solar system. Assuming that the source was from a nearby star, it implied the existence of an object emitting X-rays at a rate millions of times greater than the Sun. Only a few months after the public disclosure of this discovery, the NRL group was able to confirm the result and to report the existence of other sources. A



Riccardo Giacconi

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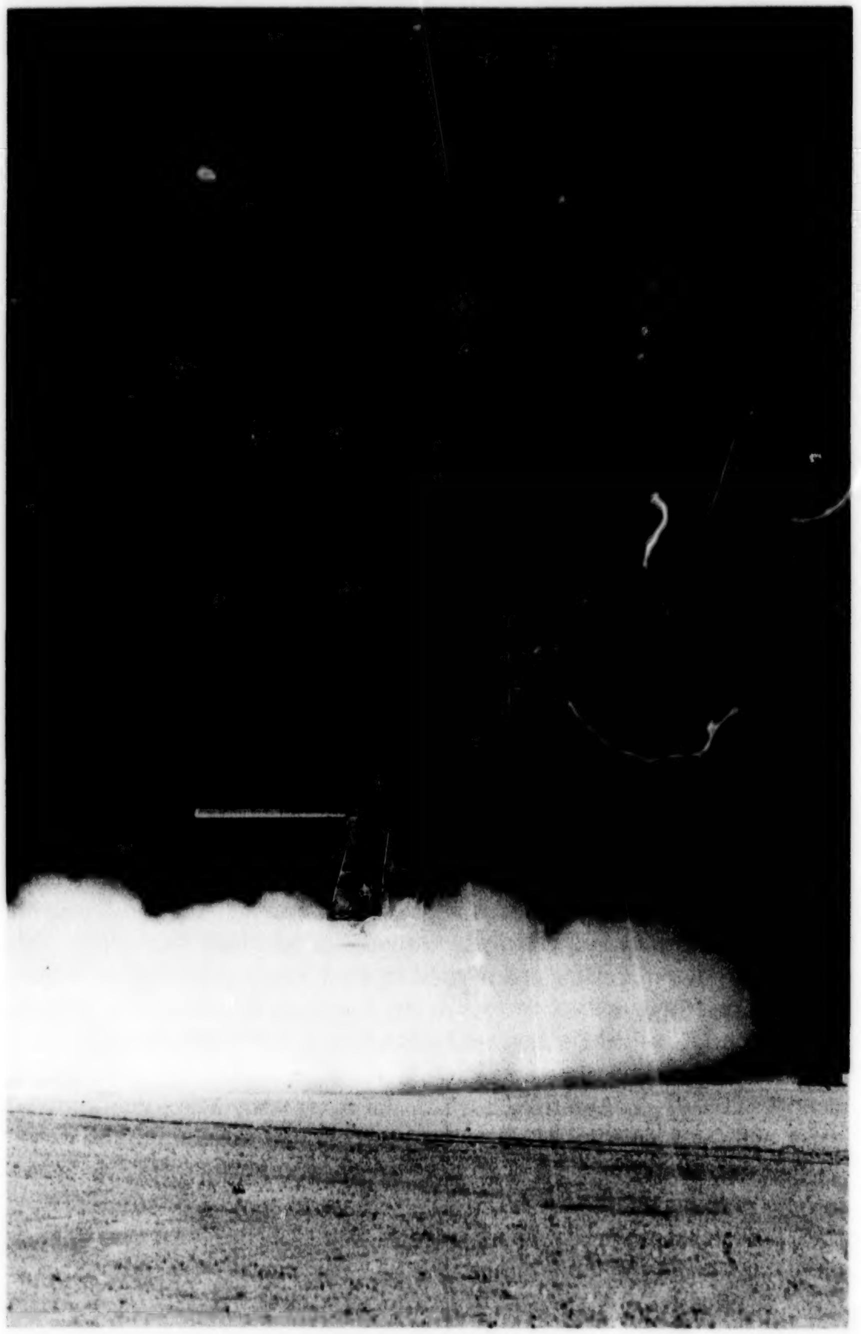

Early X-ray astronomy experiments used sounding rockets to carry X-ray detectors above the atmosphere for a few minutes. Shown here is a two-stage Nike-Tomahawk rocket with a 12-inch diameter payload designed by the X-ray astronomy group at the Lawrence Radiation Laboratory for the purpose of studying the X-ray source Sco XR-1. The rocket was launched from Johnson Atoll, September 28, 1967. (Photo courtesty Fred Seward) rich new field of research had been opened. Because the sources were so strong, they could be studied with small conventional detectors aboard rockets or, in the case of sources that produced strong fluxes at high X-ray energies, from high flying balloons.

Meanwhile, improvements in experimental techniques and the availability of small satellites had made possible significant advances in the study of cosmic rays. Observations of the relative abundance in the cosmic rays of the different nuclei and their isotopes and the discovery of an electron component in cosmic rays cast certain theories for the origin of cosmic rays in grave doubt. For example, high energy electrons should lose most of their energy in about ten million years. This makes it doubtful that these electrons were produced more than ten million light years away. Similar arguments concerning the abundance of heavy nuclei and certain isotopes of lighter nuclei restricted the possible theories of the origin and propagation of these high energy particles. Here too was a field ripe for development. One of the leaders in the field was Frank McDonald of the Goddard Space Flight Center in Greenbelt, Maryland. Frank McDonald thought the time was right to push for a large cosmic ray experiment aboard a large satellite.

To better understand how the progress down the paths blazed by Friedman, Giacconi, and McDonald eventually led to the HEAOs, let us look briefly at the way a new space mission gets started. It takes more than just a good idea, or even a great idea. It takes intense political groundwork on at least three levels.

First, there is the grass roots level, the scientific community. You must convince your peers that yours is a good idea, one that they will support both as a group and individually in committees on which they serve. This you must do by publicizing and promoting your idea in print and in person, at general meetings of such groups as the American Astronomical Society, the American Physical Society, the International Astronomical Union, and the American Association for the Advancement of Science, and before scientific advisory committees, such as the Astronomy Missions Board of NASA and the Space Science Board of the National Academy of Sciences.

Second, you must marshall support within NASA. NASA Headquarters must agree that yours is a project more worthy of support than other, competing projects. It was here that the scientists found two staunch allies who would play key roles in ensuring the success of the HEAO program. They were Richard Halpern, who would become NASA program manager for the project, and Jesse Mitchell, who was at the time the director of the Physics and Astronomy Division at NASA. Also, since all large projects must be managed by NASA, one of the NASA centers, at Huntsville, Alabama, or Greenbelt, Maryland, for example, must be willing to devote a portion of their manpower to the project.

High flying balloons carried gamma ray and cosmic ray detectors to altitudes over 100 000 feet. Shown here is the launch of MIT's High Energy X-ray (15-120 kiloelectron volts) Balloon Observatory from Australia on October 15, 1970. The 34 million cubic foot balloon carried the Observatory to an altitude of about 145 000 feet. After 10 hours of observing, the Observatory parachuted back to Earth (the parachute is visible in the picture behind the group of people). The flight became a historic one: the first slowly rotating X-ray pulsar designated GX 1 + 4 was discovered; its period was measured to be about 2.3 minutes. (Photo courtesy of Professor Walter H. G. Lewin)

Finally, Congress and the Administration must approve the funds for the project. This means that when the time comes, as it always does, to cut the budget, your project must survive. This step of the process connects back to the first stage. A staffer in the Office of Management and Budget, for example, will pick up the phone and call some eminent scientist when he has a question about a proposed space science project. If this scientist has been convinced by your early work in the hustings, you're in good shape. If not, you're in trouble.

In order for your project to fly, you must succeed at all three levels. If you fail at any one, you lose. In the words of the folk song, you must "know your song well before you start singing."

The road to the HEAO project led in the summer of 1965 to Woods Hole, Massachusetts. After the discoveries of the early 1960s, the scientific community began to take notice of high energy astrophysics as a field with great promise. Accordingly, the Space Science Board of the National

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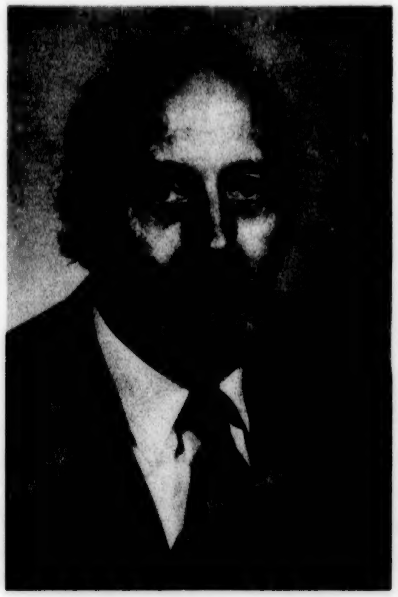
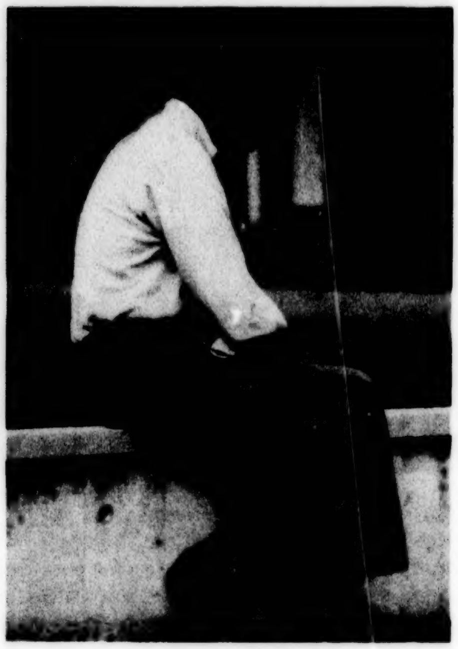


Frank B. McDonald



Richard E. Halpern

Academy of Sciences convened a summer study group that included panels on X-ray, gamma ray, and cosmic ray astronomy. From this meeting emerged a consensus among cosmic ray physicists such as McDonald, who needed heavy payloads, X-ray astronomers such as Friedman, who were interested in extremely large area X-ray detectors, and X-ray astronomers such as Giacconi, who hoped to use X-ray telescopes. These groups agreed that a large but inexpensive spacecraft could do the job. They envisioned a series of identical and relatively inexpensive spacecraft — built from leftover Apollo program hardware, for example — that could carry out the two basic types of missions: one that performs a general survey of the sky, and one that points a telescope at particular objects and studies them in detail.

After Woods Hole, the high energy astronomers went back to work, flying rockets and balloons, improving techniques, and pushing back the frontiers in a field that was attracting a growing number of talented researchers. In the meantime they continued to champion the idea of a series of large spacecrafts in letters to NASA officials, in meetings, and to the scientific community at large. It became less and less difficult to convince the scientific community of the importance of high energy astronomy as the discoveries kept coming in. The detection by the NRL group of X-rays from

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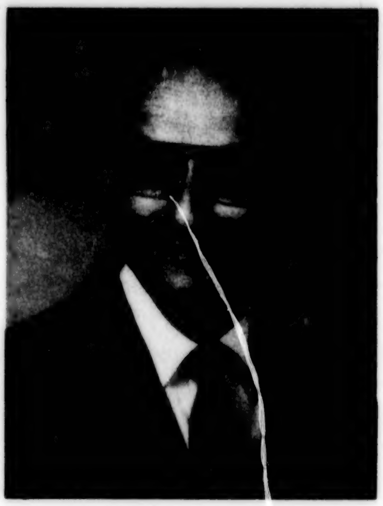
Alois Schardt

Jesse Mitchell



Carroll C. Dailey

the galaxy M87 showed that the reach of X-ray astronomy extended beyond the galaxy. Gamma ray sources were discovered, and the nuclei of very heavy elements were detected in cosmic rays.

In 1967 NASA established the Astronomy Missions Board to assist in an advisory capacity in the planning of astronomical experiments in space. This board was composed of 18 members of the scientific community with a wide diversity of interests and experience. The Chairman was Leo Goldberg, at that time Director of the Harvard College Observatory. On the board were Friedman and three other scientists who were actively involved in high energy astronomy: William Kraushaar of the University of Wisconsin, Laurence Peterson of the University of California, San Diego, and

John Simpson of the University of Chicago. Assisting the board were 31 other scientists who served on panels that studied the various subdisciplines of astronomy, such as X- and gamma ray astronomy, optical astronomy, etc. After months of study, during which the board heard presentations from supporters of various competing missions, including Dick Halpern speaking on behalf of the HEAO concept, it recommended a greatly expanded program in high energy astronomy that would include as a top priority a series of large experiments, weighing from 1000 to 5000 kilograms, and would be launched by a Centaur or Titan III-C rocket.

The endorsement by the Astronomy Missions Board was crucial. It showed that a broad spectrum of scientists approved of the HEAO concept. Funds were appropriated for a feasibility study of the HEAO concept within NASA, and Dick Halpern became program manager. He quickly went to work establishing the basic ground rules and policies, putting together a skeleton organization, and in general building a strong case for the program in government circles. Assisting him in this effort were Alois Schardt, then Chief of the Particles and Fields Division of NASA, and Frank McDonald at Goddard.

Schardt and McDonald put together a cosmic ray astrophysics committee to investigate the feasibility of putting very large cosmic ray and gamma ray experiments on satellites. Their original idea was to stack the experiments up in a nested fashion, launch them with a Titan-C, and scatter the experiments in orbit. Schardt and McDonald took this idea to Goddard Space Flight Center, which had traditionally handled space science experiments. However, Goddard was heavily occupied with space applications programs at the time, so it turned down the HEAO project. McDonald and Schardt then went to Marshall Space Flight Center in Huntsville, Alabama. At that time Marshall was primarily a rocket building center, under the direction of Werner von Braun. However, von Braun and his associates, including Ernst Stuhlinger, realized that the peak effort of the Apollo program was about over as far as rocket building was concerned. So, when McDonald and Schardt made their presentation to Stuhlinger, they had a receptive audience. Stuhlinger liked their ideas and set up a panel, including McDonald, Schardt, Carroll Dailey, Tom Parnell, Jim Downey, and Gerry Fishman, to study the concept in more detail. Dailey and his colleagues at Marshall showed that the multiple deployment idea would not work. They came up with a workable alternative, a spacecraft that was essentially a large boxcar weighing about 12 000 kilograms.

Then Frank McDonald and Carroll Dailey put together what McDonald termed a "dog and pony show" to promote the HEAO concept. They took their show to the various advisory boards. Thanks in large part to this work and the efforts of Halpern and Mitchell at Headquarters, NASA accepted the HEAO concept. In early 1970 NASA issued an Announcement of Opportunity (AO) for proposals for experiments to be flown on one of a series of High Energy Astronomy Observatory missions. The huge number of proposals received confirmed the conviction of HEAO's advocates that the program had strong support in the scientific community. Out of the proposals, four missions were formulated. The first mission would carry four X-ray experiments, two gamma ray experiments, and two cosmic ray experiments. The second mission would carry two X-ray experiments, two gamma ray experiments, and three cosmic ray experiments. The third mission would carry an array of focusing X-ray telescopes and the fourth mission would carry a group of cosmic ray experiments. Thanks to the advance work by McDonald, Dailey, Halpern, and many other scientists and engineers, the HEAO program was approved by Congress, and funding for the first two missions began in July 1971. Albert Opp of NASA Headquarters, who had been involved with the advocacy of HEAO since 1970, was named program scientist. Fred Speer was named program manager at Marshall Space Flight Center. TRW was selected as the industrial contractor for the spacecrafts. Design studies on the spacecraft and the instruments began. Six years after the Woods Hole summer study, HEAO was finally being transformed from a vision into a reality. Things went smoothly until January 2, 1973.

When Dick Halpern came to work after New Year's Day, he received a phone call. The message: work on the HEAO project was to be suspended immediately. Recalls Halpern: "After living and breathing HEAO for three years, the shock was too much. I was sick to my stomach. Literally."

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ON THE ROAD AGAIN

The decision to cancel the HEAO project was made for one reason — money. The Nixon Administration had put a lid on executive agency spending for the fiscal year 1974 budget that was less than the amount of money appropriated by Congress. This left NASA with a shortage of funds. This shortage was severely aggravated by cost overruns on the Viking program to land a spacecraft on Mars in 1976. More money — a lot more — was needed to see this important program through. Getting more money through increased appropriations from Congress was out of the question. The only recourse was to cut an existing NASA program. The only program with sufficient funds to help them out of the Viking dilemma was HEAO, a program whose escalating projected cost was causing nervous concern among NASA administrators. The cancellation of HEAO would solve two problems at once; thus, HEAO was canceled.

One lesson every successful manager learns in the hectic and uncertain world of space science is to never take the first word of cancellation of a project as the last word. Accordingly, Halpern and Mitchell set to work immediately to reverse the decision and rescue the HEAO program. Their strategy was to seek a stay of execution. They would present a scaled down version of the program, costing a third to a half as much as the original version, to the NASA administrators and try to convince them to change the status of HEAO from "canceled" to "suspended."

It was a good strategy. NASA, for a relatively modest outlay of study funds, could have a year and a half to wait and see if a workable alternative to the original HEAO program could be developed; in the meantime they could assess the mood on Capitol Hill and in the scientific community as to whether the project was really worthwhile. The scientists and HEAO program people, for their part, would have a year and a half to make their case.

There was a case to be made, especially in X-ray astronomy. NASA's X-ray Explorer satellite, nicknamed UHURU because it had been launched from Kenya on that country's independence day, had proven to be a tremendous success. UHURU, which was under the scientific direction of Riccardo Giacconi and his X-ray astronomy group at AS&E, was part of NASA's Explorer Program of Small Astronomy Satellites devoted to a single mission. It was the first satellite to be devoted entirely to X-ray astronomy. For the first time, a detailed and accurate map of the X-ray sky was available. Also for the first time it was possible to monitor individual sources of X-rays for prolonged periods of time. The result was a breakthrough in the

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understanding of these sources. Some X-ray sources were shown to be neutron stars in tight orbits around supergiant stars, others were shown to be giant clouds of hot gas between galaxies, and at least one object, Cygnus X-1, provided the strongest evidence to date for the existence of black holes. One measure of the interest generated in the scientific community by the discoveries of UHURU: the UHURU catalog of X-ray sources was cited more than any other scientific paper in the year it was published.

Against this background, Halpern and Mitchell worked almost continuously for three days to put together a new version of HEAO. Weight considerations were paramount, because the more weight put into orbit, the more it costs. Accordingly, they decided to replace the original four large spacecraft with three smaller spacecraft, each having a total weight of about a third that of the original spacecraft. Thus, instead of putting around 40 tons in orbit as originally planned, they would put only about ten tons up, or about three tons per experiment. This meant that the large and heavy high energy cosmic ray and gamma ray experiments had to go. In view of the successes of UHURU, it was decided to play the strong suit first: the first two spacecraft would be devoted to X-ray astronomy and the third to smaller cosmic ray and gamma ray experiments that could fit within the stringent new weight requirements. The experiments to fly on the first HEAO would be those X-ray astronomy experiments from the original two HEAOs that could be fit into a smaller spacecraft.

On Friday, January 5, 1973, Fred Speer, HEAO project manager at the Marshall Space Flight Center, and the Principal Investigators at various institutions in the United States and Europe were notified of the suspension of HEAO. They were told to stop work on the project and were called to a meeting in the near future to see if a rescue operation was possible. In the meantime, Jesse Mitchell began to work his contacts in the NASA hierarchy. He did this partly through force of argument and partly, according to some sources, through the threat of his resignation. A person crucial to the success of Mitchell's efforts was Richard McCurdy, who was at that time an Associate Administrator for External Affairs and an influential member of the ranks of upper management. In the seven weeks between January 2 and February 20, Mitchell was able to convince McCurdy that NASA should not cancel the HEAO program outright, but rather that they should suspend it for eighteen months and take another look at it then.

In the meantime, the scientists were reacting to the news of what came to be called "Black Friday." Hale Bradt's reaction was to fly to Tucson, Arizona, where the executive council of the American Astronomical Society was meeting. With the help of MIT colleague Bernie Burke, who was a member of the council, he urged the council to draft a resolution that stressed the importance of the HEAO program for progress in astronomy and protested its cancellation. Recalls Bradt, "I'm not sure it did any good, because we didn't do the next step, which was to have the resolution

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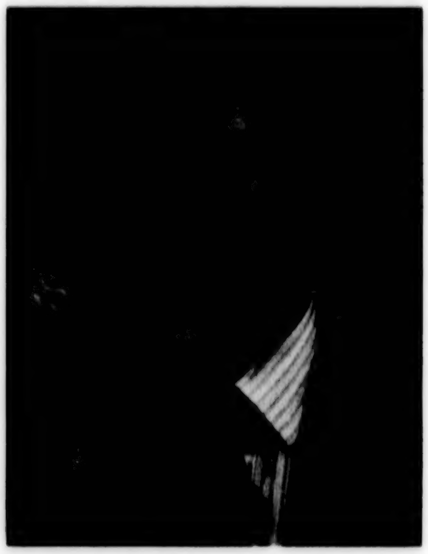
Dr. Fred A. Speer



Dr. Albert G. Opp

published in some magazine such as *Physics Today* or *Science*. Maybe it had a little effect, but I doubt it." Al Opp, who along with Al Schardt and Fred Speer played a key role in helping Halpern and Mitchell restructure HEAO, disagrees. "The AAS resolution was exceedingly important in keeping HEAO alive."

Early in 1973, the principal investigators on the old HEAOs were called to a meeting at NASA at which the restructured HEAO program would be presented to them for the first time. Walter Lewin of MIT remembers the meeting vividly. "The meeting had the atmosphere of a funeral. No one knew for sure who was going to be on, and who would lose his head. Then Jesse Mitchell gave this speech about a tree and manure, and that there was smell from the manure yet something good was happening to the tree. Incredible. Then he was talking about a boat that was sinking. You could drown, or swim to shore and find another life, or swim along and push the boat. I couldn't believe it."

After Mitchell's speech, the scientists were told who was on and who was off. The meeting then became, by some accounts, "rather heated," by others, "chaotic." In the meeting room and in the halls during the breaks, the scientists argued their cases forcefully and scrambled to stay on board or to get on board, if there was a glimmer of hope. For some, there was no hope. Their experiments simply were too heavy to be accommodated on a spacecraft that could weigh at most 7000 pounds, down by a factor three from the original mission. This was the fate of most of the cosmic ray and gamma ray experiments. For many of the X-ray experiments, however, there was still room for negotiation and compromise, and the pressure to

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Before restructuring, two large HEAO missions had been funded. Several members of the scientific and engineering teams for these missions posed for this photograph at NASA headquarters. Left to right: Richard Halpern, Edward Stone, Martin Israel, Joseph Klarman, W. R. Binns, unidentified, C. J. Waddington, Tom Parnell, Wolfgang Schmidt, unidentified, Frank McDonald, Walter Lewin, Richard W. Huggett, Herbert Gursky, John Ormes, Michael Pelling, James Matteson, Robert Farnsworth, Robert Novick, Gunther Riegler, and Talbot Chubb. (Photo courtesy of Walter H. G. Lewin)

make deals became tremendous. Stuart Bowyer, a strapping six footer whom no one has ever accused of being shy, remembers, "I was standing there in the hall talking to Al Opp about my experiment, when this guy who I had always thought of as a quiet sort comes up and literally pushes me out of the way so he could get his pitch in first. I couldn't believe it!"

In this and similar meetings over the next few months, the new HEAOs began to take shape. Much of the same road had to be traveled again. Scientific advisory groups had to approve, the spacecraft contractor, TRW, had to be consulted, and the scientists and engineers at Marshall Space Flight Center and at the various universities and laboratories involved had to come to an agreement as to what was scientifically desirable and what was practical, given the smaller spacecraft and the smaller budget.

Many scientists and engineers contributed to this effort. Halpern singled out Richard Whilden of TRW for special praise. "Dick Whilden and his group were instrumental in the success of the restructuring. He put together a very, very classy team of engineers, and they worked very long and hard with Fred Speer and me to get a new program."

Among the beneficiaries of the negotiation and restructuring period were Walter Lewin and Larry Peterson, who had argued the importance of including a high energy X-ray experiment on HEAO. Mitchell, Opp, and Schardt apparently agreed with their arguments, because, according to a grateful Lewin, "Al Opp and Al Schardt were instrumental in getting a high energy X-ray experiment back on board rather rapidly."

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A gathering of HEAO Principal Investigators. Front row, from left: Herbert Gursky, Talbot Chubb, Riccardo Giacconi, Lydie Koch-Miramond, Martin Israel, Edward Stone. Back row, from left: Hale Bradt, Frank McDonald, C. J. Waddington, Allan Jacobson, Walter Lewin, Elihu Boldt, James Matteson.

During this period, two X-ray telescopes had flown aboard Skylab. These telescope experiments, which were directed by G. Vaiana and J. Underwood, had made stunning X-ray images of the Sun. These pictures impressed the HEAO planners. They proved that focusing X-ray telescopes were no longer a somewhat risky and premature concept. They worked spectacularly well on Skylab and, if flown on a HEAO mission, would very probably provide the next breakthrough in X-ray astronomy. Accordingly, the focusing X-ray telescope proposed by a consortium of scientists from Harvard-Smithsonian Center for Astrophysics, MIT, Goddard Space Flight Center, and Columbia University was chosen for the second HEAO mission, HEAO B. Riccardo Giacconi, who had moved from AS&E to the Center for Astrophysics, was to be the Principal Investigator. Steve Holt of Goddard Space Flight Center would oversee the project as Project Scientist.

The first mission, HEAO A*, would be a scanning mission that would survey and map X-ray sources throughout the celestial sphere over a wide range of X-ray energies. It included four instruments: (1) a large area survey experiment, with Herbert Friedman as Principal Investigator, (2) a cosmic X ray experiment sensitive to a wide range of X-ray energies, with Elihu Boldt of Goddard and Gordon Garmire of the California Institute of Technology as Principal Investigators, (3) an experiment to determine the positions and structure of sources, with Herbert Gursky of the Center for Astrophysics and Hale Bradt as Principal Investigators, and (4) an experiment to study the high energy X-ray and low energy gamma ray emission

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*It has been NASA practice to designate satellites and probes alphabetically throughout the planning and production stages prior to launch and numerically as soon as they are successfully launched. Thus, HEAO A became HEAO 1 immediately upon reaching orbit; HEAO B became HEAO 2; and HEAO C became HEAO 3.

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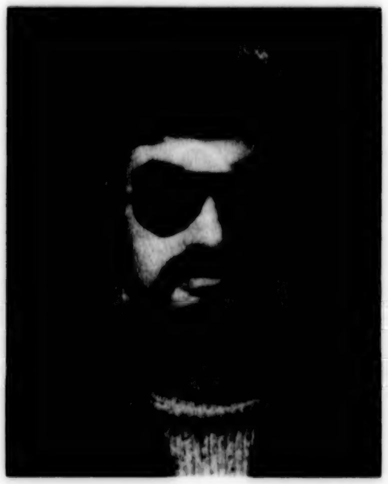
Stephen Holt



Tom Parnell

from cosmic sources, with Laurence Peterson and Walter Lewin as Principal Investigators. Frank McDonald would be the Project Scientist.

The third and final mission, HEAO C, would carry three experiments: (1) a high spectral resolution gamma ray spectrometer to explore for sources of gamma ray line emissions, with A.S. Jacobson of the NASA Jet Propulsion Laboratory as Principal Investigator, (2) an experiment to measure the isotopic composition of cosmic rays, with L. Koch-Miramond of the Center for Nuclear Studies, Saclay, France, and B. Peters of the Danish Space Research Institute as Principal Investigators, (3) an experiment to observe rare, high atomic number nuclei in cosmic rays, with Martin Israel of Washington University, St. Louis, Missouri, E. Stone of the California Institute of Technology, and C.J. Waddington of the University of Minnesota as Principal Investigators. Tom Parnell of Marshall Space Flight Center would be the Project Scientist for HEAO C.

The restructuring period was, in the words of Al Opp, "an agonizing and very painful time." Cosmic ray and high energy gamma ray astronomy received tremendous setbacks, as did the dreams and careers of many scientists, through no fault of their own. Yet from the ashes of the old program came three tightly planned, well thought out missions that would greatly advance our understanding of the high energy universe. NASA Administration approved the restructured missions, and in July 1974 major funding began. HEAO was on the road again.

5
MISSION PLANNING

Once the barrier for mission approval and funding has been surmounted, three more hurdles must be cleared before a mission can be considered a success: the instruments must be built, they must be put in orbit, and they must collect and transmit useful scientific data back to Earth. These objectives cannot be achieved in isolation. Rather, they are all intertwined, and plans in one area must be carefully orchestrated with those in the others.

Once the overall budget for the program has been set, the type of launch vehicle to use is more or less determined. It is the smallest one that can safely put the payload in orbit. For HEAO, the launch vehicle chosen was the Atlas-Centaur. This, in turn, limits the satellite volume and weight. The Atlas-Centaur rockets are built by General Dynamics Convair Aerospace Division under the direction of NASA's Lewis Research Center in Cleveland, Ohio. The Atlas is powered by three engines – two Rocketdyne engines providing 1 646 500 newtons (370 000 pounds) of thrust and one Rocketdyne engine with 267 000 newtons (60 000 pounds) of thrust. All three engines operate on liquid oxygen and RP-1 propellants. The Centaur upper stage is powered by two Pratt and Whitney engines with a total thrust of 133 500 newtons (30 000 pounds). These engines operate on liquid oxygen and liquid hydrogen. The total height of the HEAO Atlas-Centaur space vehicle ready for launch is 39.9 m (131 feet) with a total launch weight of 165 tons, of which the spacecraft plus experiments consist of three and a half tons, including one and a half tons for the experiments.

The spacecraft that carried the HEAO experiments was built by TRW Systems of Redondo Beach, California. Dick Whilden directed the TRW effort from the planning phase through the launch of HEAO-1. After the launch of HEAO-1, Whilden left the program to become Vice President and General Manager of the Test and Field Operations Division. Marshall Novick became the HEAO Program Manager for TRW and, in the words of Halpern, "played a key role in seeing the program through to a successful conclusion." TRW's role was to design and develop the HEAO spacecraft, to integrate the missions, to support launch operations at the Kennedy Space Center, and to perform flight operations of the in-orbit observatories in the mission control center at Goddard Space Flight Center. By all accounts, the performance of TRW was nothing short of outstanding. Patrick Henry of the Smithsonian Observatory spent eight months at TRW coordinating the integration of the HEAO-2 scientific instruments with the

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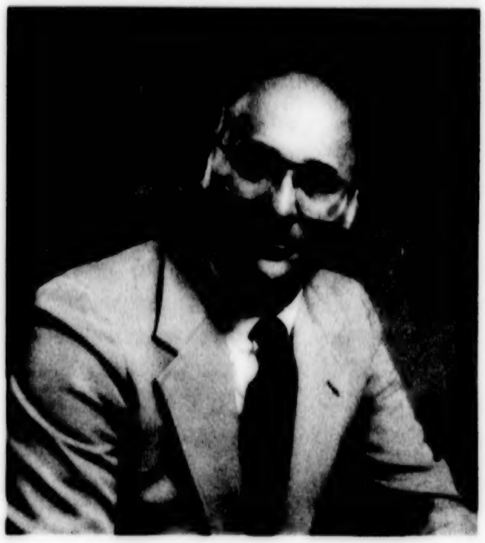
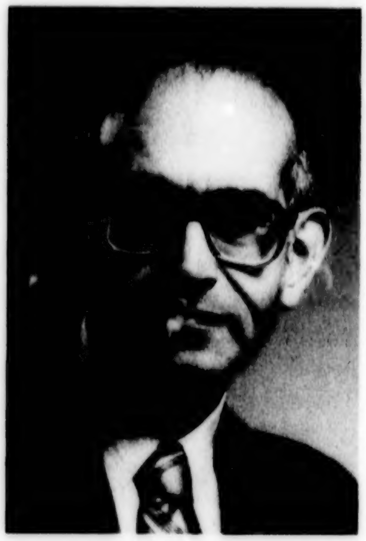


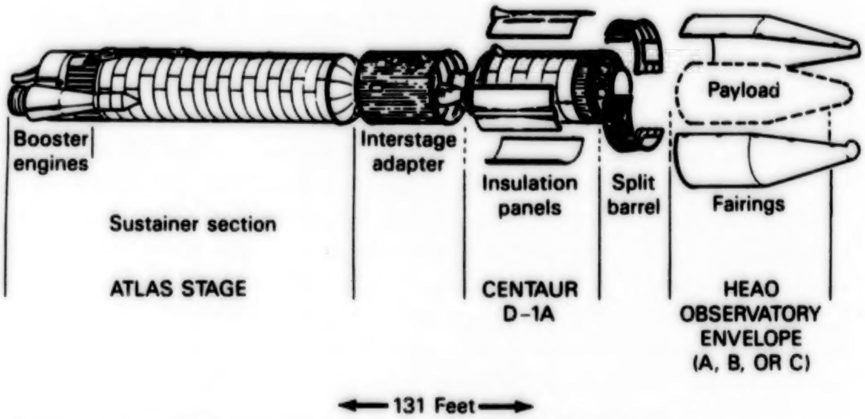
Richard D. C. Whilden



M. W. Novick

spacecraft. His impression was typical of many of the HEAO scientists: "They were very good. I was amazed that a large company could do things so well." On March 10, 1978, the National Aerospace Club in Washington, D.C., honored TRW with the prestigious Nelson P. Jackson Aerospace Award for its work on the HEAO program.

The basic subsystems design of the spacecraft was the same for all three HEAO missions, with minor exceptions to accommodate unique experiments or mission requirements. The spacecraft subsystems were designed so as to take advantage of existing hardware designs developed in other spacecraft programs. About 80 percent of the HEAO spacecraft hardware is "off the shelf."


Booster engines
Interstage adapter
Sustainer section
ATLAS STAGE
Insulation panels
Split barrel
CENTAUR D–1A
Payload
Fairings
HEAO OBSERVATORY ENVELOPE (A, B, OR C)
131 Feet

Schematic of Altas-Centaur D-IA, the launch vehicle for HEAO.

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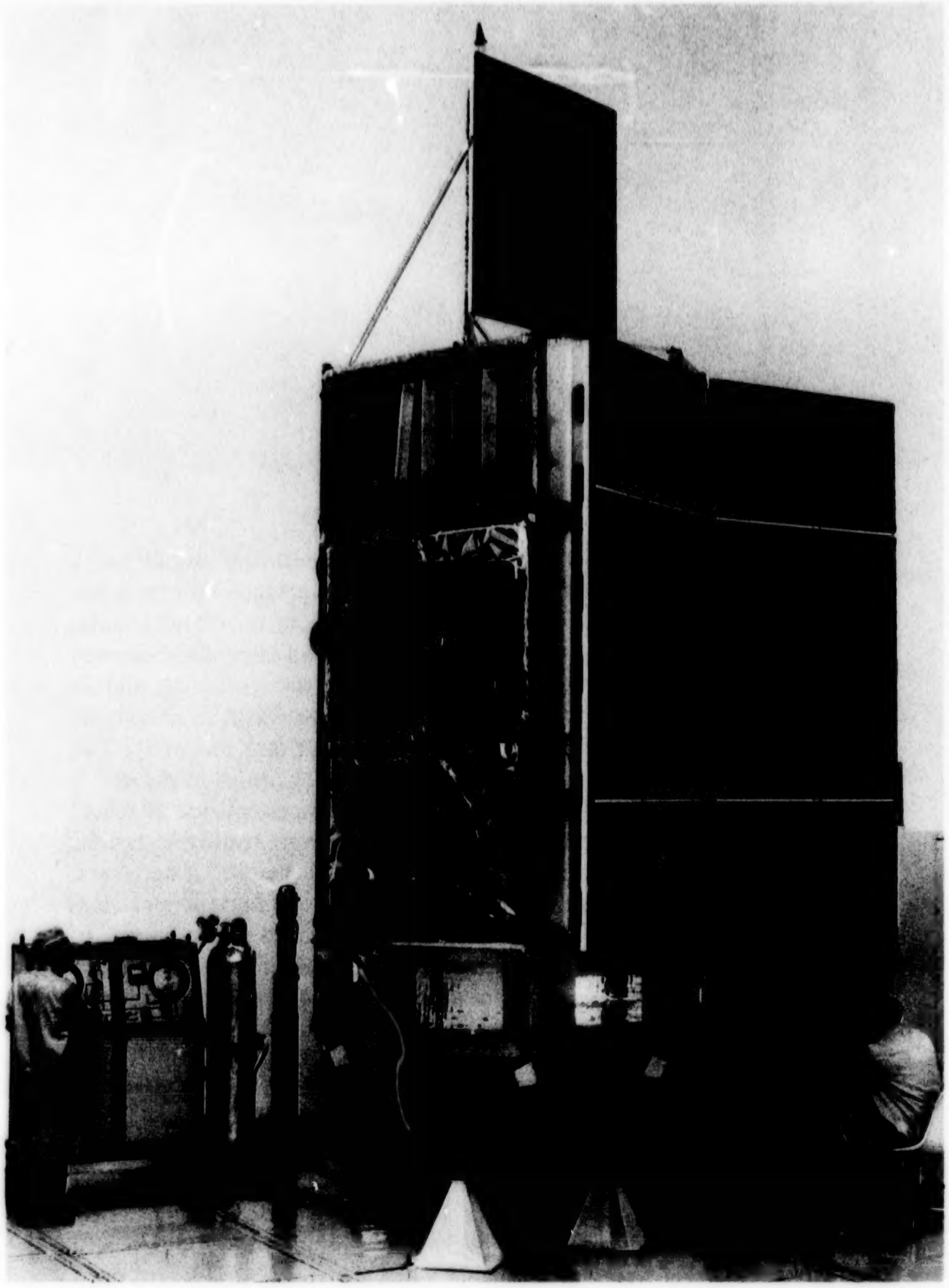

Engineers check out the first HEAO. The large wing-like structures on the top and the right side are solar panels that provided about 400 watts of power to run the observatory. (TRW photo)

HEAO 2 is prepared for flight.

The satellite consisted of two main parts, an experiment module and a spacecraft equipment module. The latter was an octagon-shaped prism about 1 m tall and 2.5 m in diameter, roughly the size of a large circular table. This module remained essentially the same on all three observatories, supplying the support systems needed to operate the spacecraft and its scientific experiments. In the center of this structure was a rigid cylinder that contained the reaction control system propellant tank assembly. This gas was used to control the motion of the spacecraft by means of gas jets. A closed honeycomb structure, to which electronic components are attached, surrounded the central cylinder. These components were readily accessible, so they could be checked during preflight testing and removed if necessary. They were distributed so as to maintain thermal equilibrium and mass balance. The spacecraft equipment module was attached to the bottom of the experiment module. The overall length of the observatories, that is, the spacecraft equipment and experiment modules, was about 19 feet, roughly the size of a small truck. Solar panels produced about 400 watts of power to run the equipment on the spacecraft.

The observatories were controlled in orbit from the HEAO Operations Control Center at Goddard Space Flight Center. Data were collected by the observatories and stored in onboard tape recorders. These were then transmitted to tracking sites and from there back to Operations Control Center. The two tape recorders on the spacecraft provided sufficient storage capacity to accumulate data for more than four orbits without dumping if the ground stations were not available when the spacecraft passed over. Control of the observatories in orbit was directed by the Marshall Space Flight Center through flight control engineers assigned to Goddard. Flight control operations were executed by TRW personnel under the direction of

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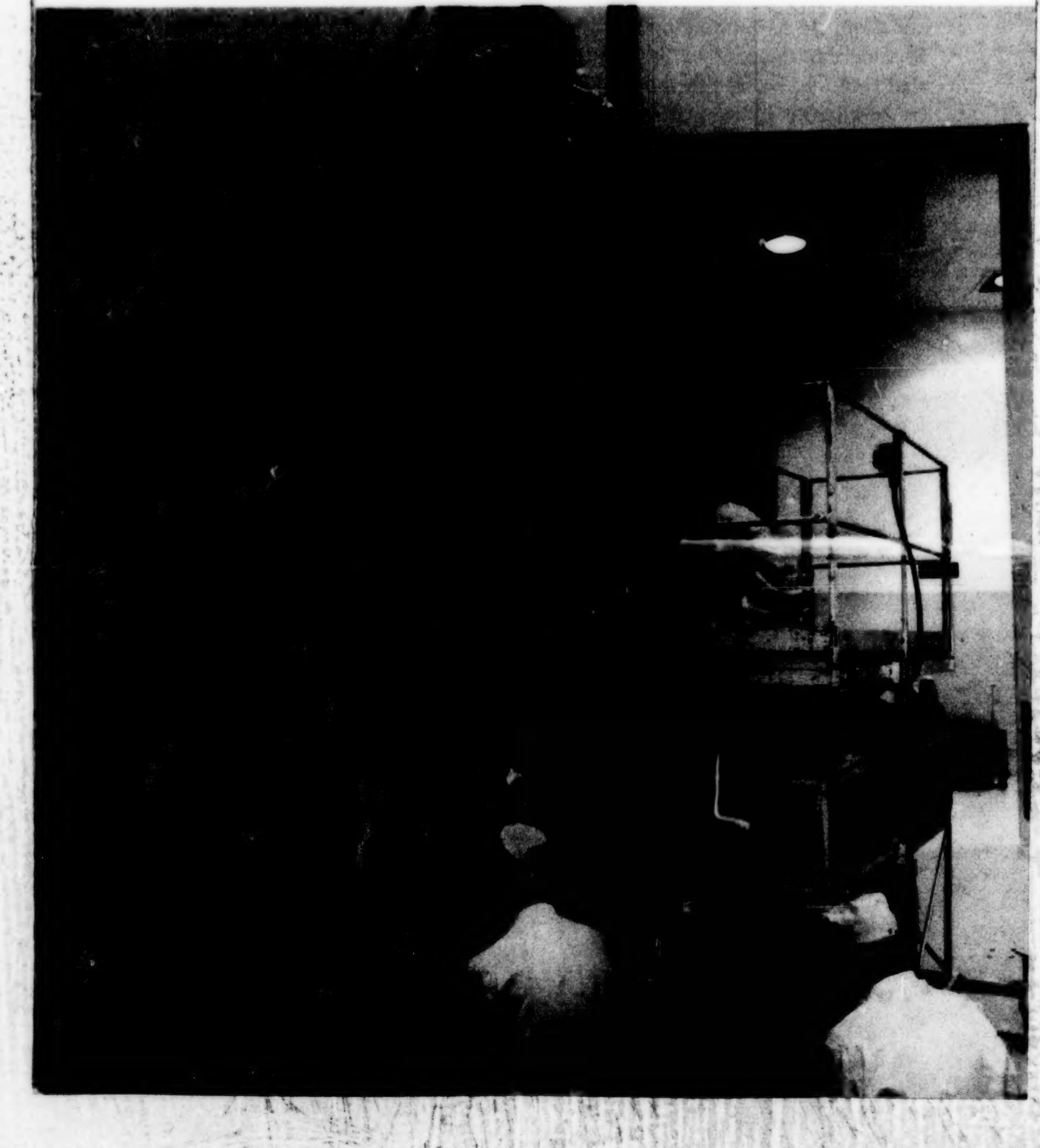
the Marshall flight director supported by scientists associated with each mission.

An onboard computer, common to all three observatories, allowed the orientation of the spacecraft to be controlled automatically. In the event of a critical power loss, a low-voltage sensor automatically commanded the observatory into a contingency mode in which the orientation could be controlled based on Sun sensor data only. This ensured the survival of the observatory until the source of difficulty could be determined by ground control.

HEAO 3 undergoes preflight checks.



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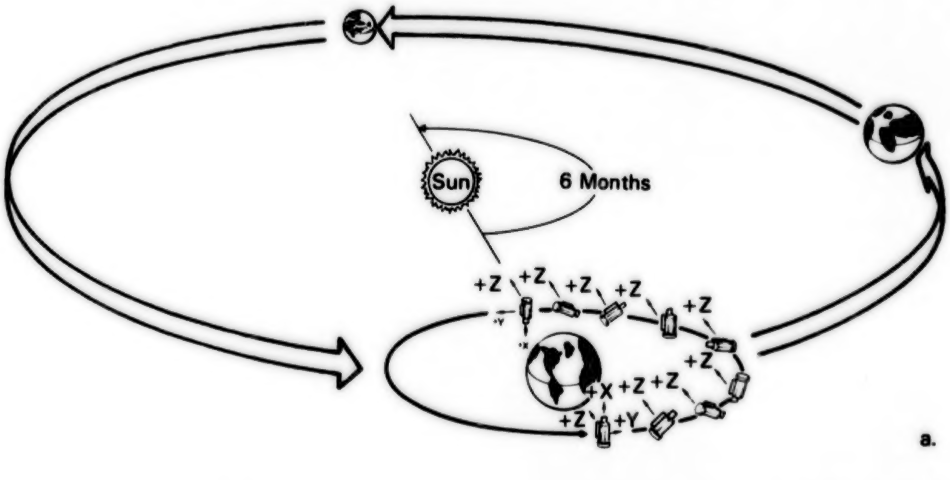
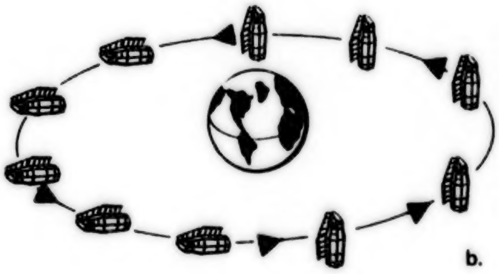
The spacecraft were placed in low circular orbits, about 300 miles above Earth. HEAO A and HEAO C were scanning missions, designed to perform all-sky surveys. They rotated slowly end over end, with one revolution about every 30 minutes, spinning in such a way that the solar arrays always pointed at the Sun, and the entire sky was scanned in six months. HEAO B, with its X-ray telescope, needed precise and highly accurate pointing capability. This was achieved by a set of rotating precision wheels that provided the desired orientation by minute changes in their rate of rotation. Star trackers were used to find known reference stars and thereby determine points of reference in the sky.

The most serious restriction in the revised program was the imposition of a fixed life on all three HEAOs. This policy was adopted in an effort to cut down on program scope and budget requirements. In practice, a fixed lifetime was ensured by the limited amount of propellant for the gas jets that could be carried by the spacecraft. Once the gas was used up, it would be impossible to control the orientation of the spacecraft in the face of destabilizing gravitational and magnetic forces, and its useful lifetime would come to an end. Other satellites had used magnetic torquing systems to orient the spacecraft; in these systems magnetic fields are applied to bars





Orbital orientation for the HEAOs. (a) HEAO 1 and 3 slowly tumbled end over end as they scanned the sky. A full celestial scan was completed in six months. (b) HEAO 2 was a directable mission, so it would point at specific sources for as long as a day at a time. All observatories were oriented to keep their solar panels directed toward the Sun for as much time as possible.

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in the spacecraft, causing it to turn. These were rejected because they are not fail-safe. If the solar panels were not pointed toward the Sun every five hours, the batteries on the spacecraft would run down. It was feared that the magnetic torquing system would be too slow, and a failure would result. A backup system of gas jets would be needed; this would increase the cost; thus, the magnetic torquing system was rejected. Later efforts were made to include a low-cost magnetic torquing system for HEAO B. It was argued that this mission, with its focusing X-ray telescope, might be worth prolonging for several years. The request was not granted, so another tactic was used to prolong the lifetime of the observatory. HEAO scientists Ethan Schreier and Harvey Tananbaum of the Smithsonian Astrophysical Observatory, together with Marshall Space Flight Center engineers Tom Recio and Tom Guffin, conceived and implemented an ingenious momentum management program. This plan minimized the use of gas by selecting optimum times to observe specific targets and deleting targets in unfavorable positions. As a result, the lifetime of HEAO B was extended to more than two and a half years from the originally planned one year.

Spacecraft such as the HEAOs have thousands of components, any one of which could fail in orbit; some of them undoubtedly will fail in orbit. The key to a successful mission is to design the spacecraft and the experiments such that a single failure cannot cause the loss of a substantial portion of the mission's scientific objectives. This is the principle of "soft failure." In order that the inevitable failures be "soft" rather than "hard,"

Control Center at the NASA-Goddard Space Flight Center. (Photo by Dane Penland; Smithsonian Institution Photo No. 80-18165)

all critical components should be redundant. During the early design phase of HEAO, single failure point analyses were performed to identify all mission failure points. When the analysis indicated that mission failure could be avoided by redundancy, one or more extra components was added. Most instruments had a high degree of modularity, which was built-in insurance against single failure points. For example, an X-ray detector might have several modules, and the failure of any one of the modules would not affect the performance of the others. By the same token, the individual instruments were designed to be independent of one another as much as possible, so that a failure of one instrument would not jeopardize the performance of the others. Extra gyroscopes, tape recorders, star trackers, etc., were added to the spacecraft. Once the redundant components were added, they were checked time and again until launch to make sure that redundancy still existed on launch day.

6

THE STAR SPLITTERS

The instruments that flew aboard the HEAOs have allowed us to split, or analyze, the radiation from stars and galaxies in a special way. By using a carefully chosen complement of detectors to study the various aspects of high energy cosmic radiation, they have given us a glimpse of the hot spots in the universe. They allow us to probe regions of space where particles have been raised to very high energies by strong magnetic fields, violent explosions, or intense gravity.

The HEAO 1 mission carried an array of independent but complementary experiments designed to survey and map X-ray sources throughout the celestial sphere. The instruments had the capability of locating X-ray sources and studying their variation in time and the distribution of their radiation with energy over a broad range of X-ray energies. HEAO 3 carried three instruments designed to survey the sky for cosmic sources of gamma radiation and to take samples of cosmic rays, the high energy particles that reach Earth from outside the solar system. HEAO 2 was the most complex of the missions. It carried a large X-ray telescope that produced the first detailed X-ray images of objects outside the solar system. These images were analyzed by interchangeable instruments at the focal plane of the telescope.

Building an instrument for astronomical observations is never easy, because astronomers push instrument technology to the limit as they try to wring yet another drop of information from some distant source on the dim boundary of observability. As Herb Friedman put it, "There is no better way to check an instrument than through astronomy. Building an instrument for space astronomy is triply difficult. The scientists and engineers working on the HEAO missions not only had to cope with technology pushed to the limit, or in some cases invent new technology. They had to work with the knowledge that once the spacecraft was launched, it would be gone. There would be no possibility of recalling the spacecraft to work out the bugs. It had to be done right the first time. On top of this, they had to put the missions together on a tight budget, and to stay on a tight schedule, because, on a project such as HEAO, time was money'."

All these factors made HEAO, in the words of Tom Parnell, project scientist for HEAO 3, "an ulcer generating business." Adding to the tension was the ever present possibility of cancellation. "I always felt like we were on the brink of cancellation," said Claude Canizares of MIT, a member of the consortium of scientists that worked on HEAO 2, "either in terms of a

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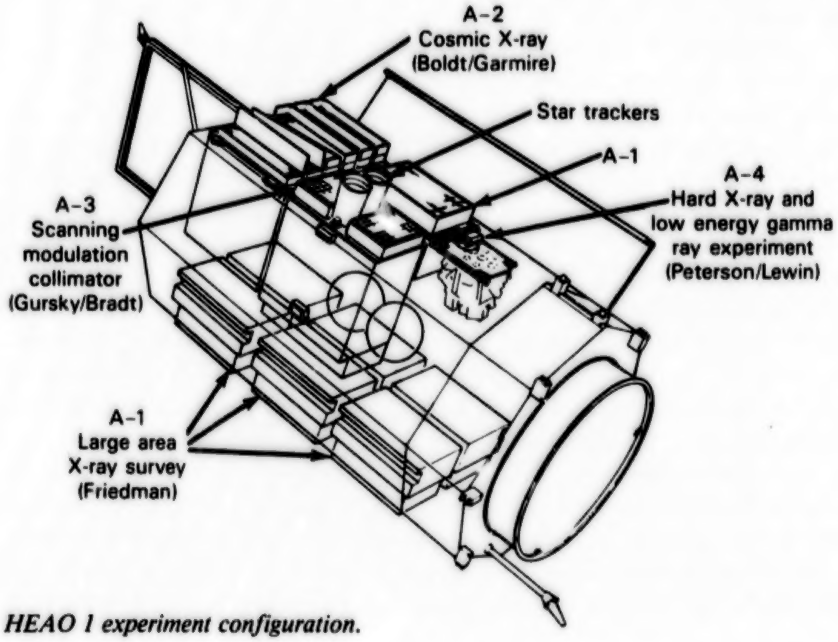
whole project or our individual experiment." According to Al Opp, NASA program scientist for HEAO, Canizares' feelings were not realistic. "HEAO was always a problem because it was always a little underfunded. . . . HEAO 2, with its exceedingly sophisticated, exceedingly complicated optical system, was the most difficult. It was a larger and more difficult mission than everyone had estimated. It was very difficult to keep the cost down and keep the mission intact at the same time."

NASA's understandable concern to keep close to budget caused worries among the scientists that NASA was being penny wise and dollar foolish. "There's a cost effectiveness threshold," Dan Schwartz of the Center for Astrophysics, who became one of the principal investigators on HEAO 1, observed. "If you don't do it with a certain quality, you get nothing. I felt that NASA was always pushing that threshold." Another scientist termed this the bridge builder's philosophy, according to which "They seemed to have the point of view that whereas it would be a disaster to build a bridge an inch too short, it would be silly to make it a foot too long. They very much stuck to the minimum requirements, when a little extra might have yielded a substantial gain in quality." Other scientists seemed to worry that NASA might misjudge how long the "bridge" would have to be and were thereby courting disaster. On the other hand, many took the point of view of Walter Lewin, who felt that things would never quite get that bad if the principal investigators were sufficiently vocal. "The responsibility for the integrity of the experiment is in the final analysis on the PI's shoulders. If he


A-2
Cosmic X-ray
(Boldt/Garmire)
Star trackers
A-1
A-4
Hard X-ray and
low energy gamma
ray experiment
(Peterson/Lewin)
A-3
Scanning
modulation
collimator
(Gursky/Bradt)
A-1
Large area
X-ray survey
(Friedman)

HEAO 1 experiment configuration.

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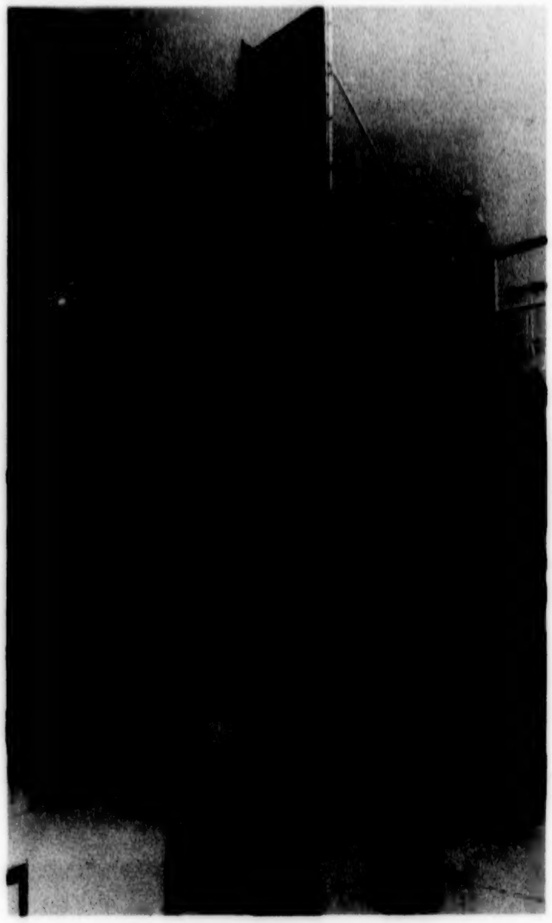
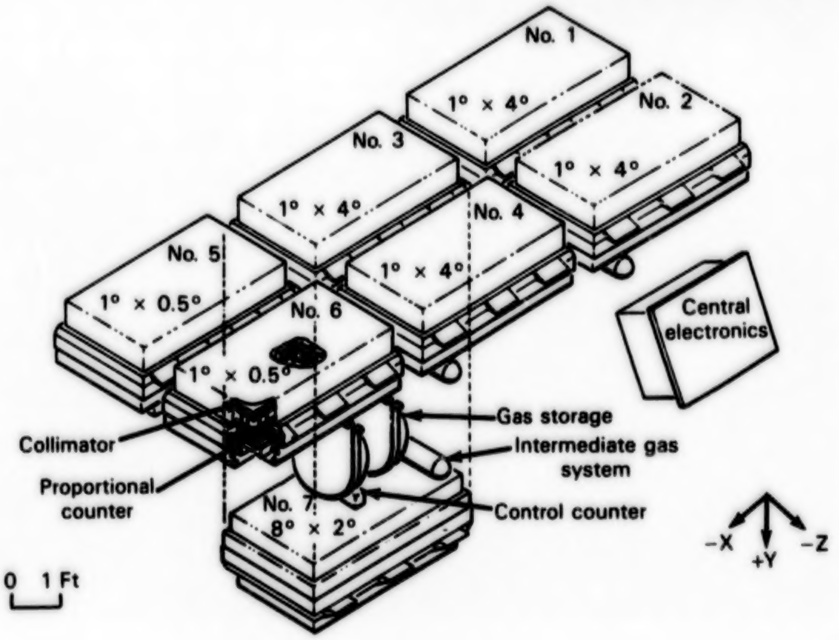


HEAO A-1 Experiment, the Large Area X-ray Survey Experiment. The A-1 experiment consisted of seven modules of thin window X-ray proportional counters, central electronics, two stellar aspect assemblies, and a gas system. The major purpose of the experiment was to map the celestial sphere for X-ray sources and to determine the spectrum, intensity, and time variations of the radiation from these sources. The Principal Investigator for A-1 was Herbert Friedman of the Naval Research Laboratory (NRL). Hardware was produced by NRL with assistance from New Mexico State University, Las Cruces.


No. 1
1° × 4°
No. 2
1° × 4°
No. 3
1° × 4°
No. 4
1° × 4°
No. 5
1° × 0.5°
No. 6
1° × 0.5°
Central electronics
Gas storage
Collimator
Intermediate gas system
Proportional counter
No. 7
8° × 2°
Control counter
−X
+Y
−Z
0 1 Ft

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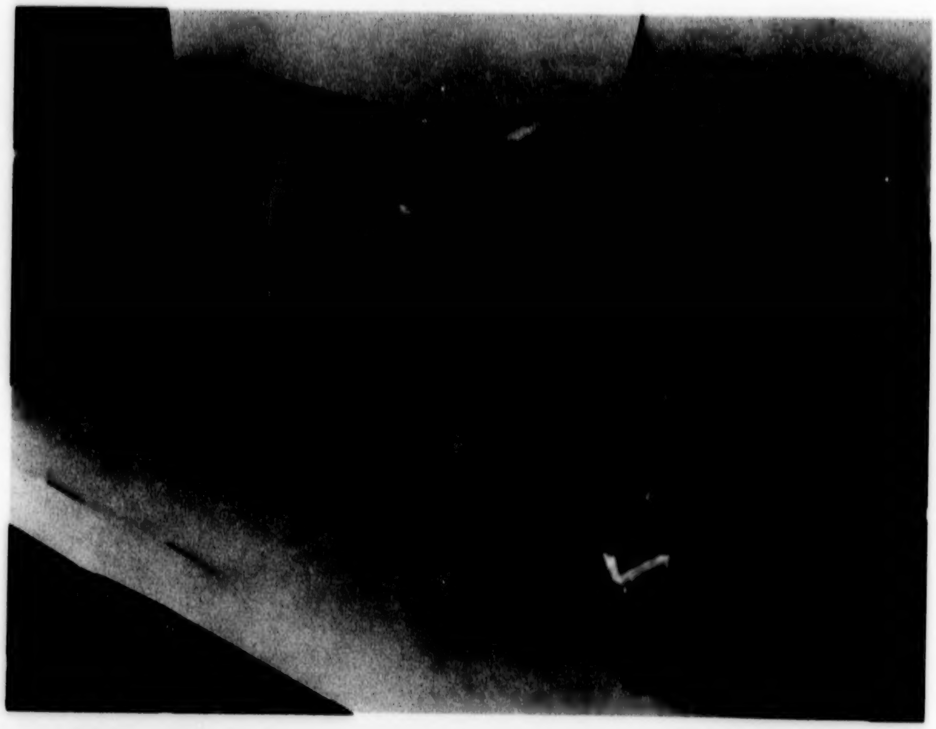

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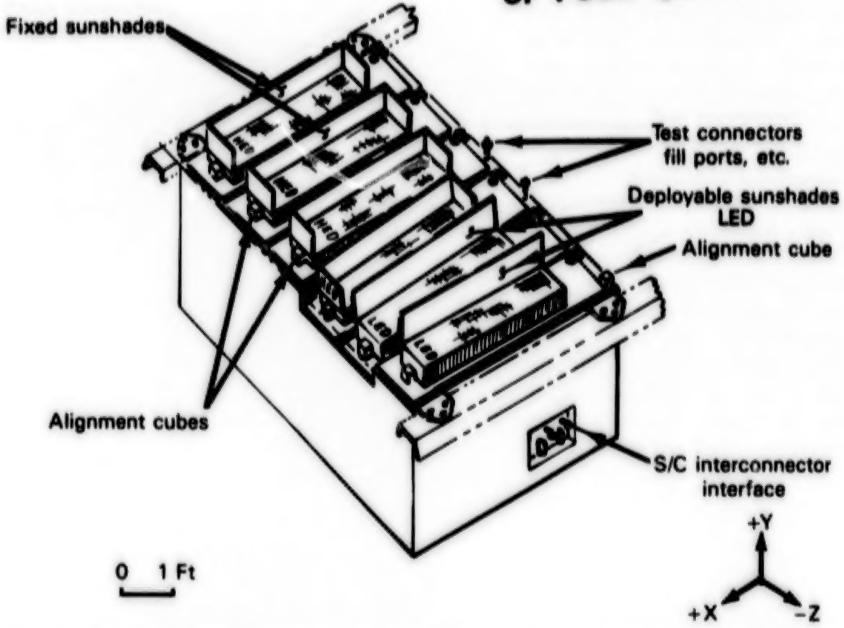

The Cosmic X-ray Experiment, HEAO A-2. The A-2 experiment consisted of six collimated detectors of thin window X-ray proportional counters, electronics, and a gas system. The major purpose of the experiment was to measure the emission and absorption of cosmic X-rays in the energy range of 0.2 to 60 kiloelectron volts. Principal Investigators were Elihu Boldt of Goddard Space Flight Center and Gordon Garmire of Pennsylvania State University. Hardware was produced by Goddard. Others assisting in the program were the Bendix Corporation, the University of California, and the California Institute of Technology.

screams loudly enough, then NASA will do what is needed." Jim Matteson of the University of California at San Diego, who worked on HEAO 1, had the same feeling. "Dick Halpern once told us to do it with as little money as possible, but not to sell the farm. I never quite knew what he meant by that, but I took it to mean that if things got desperate, the extra money would be found."

One example of this was the effort to upgrade HEAO 1 so that it would have pointing capability. Hale Bradt realized that HEAO 1 could do a much better job if only it had the ability to point at specific sources rather than just scan over them. But it would take more money. Fortunately, Bradt, with good foresight, realized the importance of a pointing capability early in the program and was able to convince the NASA officials, especially Dick Halpern, of its value. By modifying the budget in other areas, Halpern created a reserve fund to cover the extra cost of installing the necessary gas jets to give HEAO 1 a pointing capability that greatly enhanced the value of the mission.

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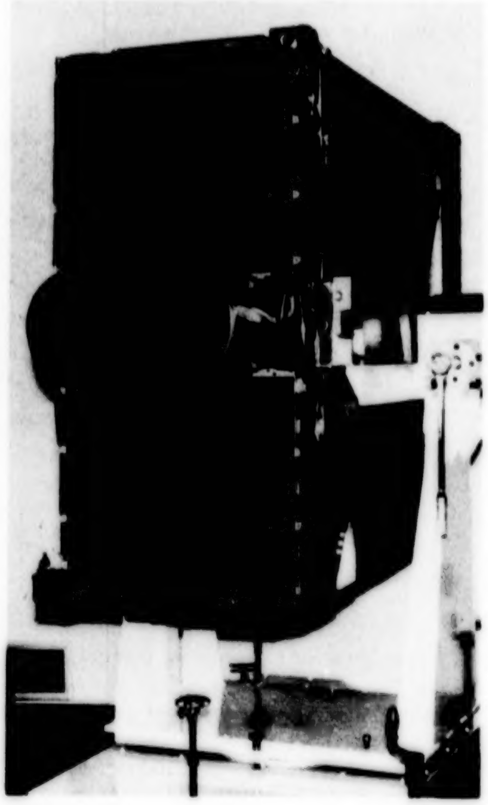
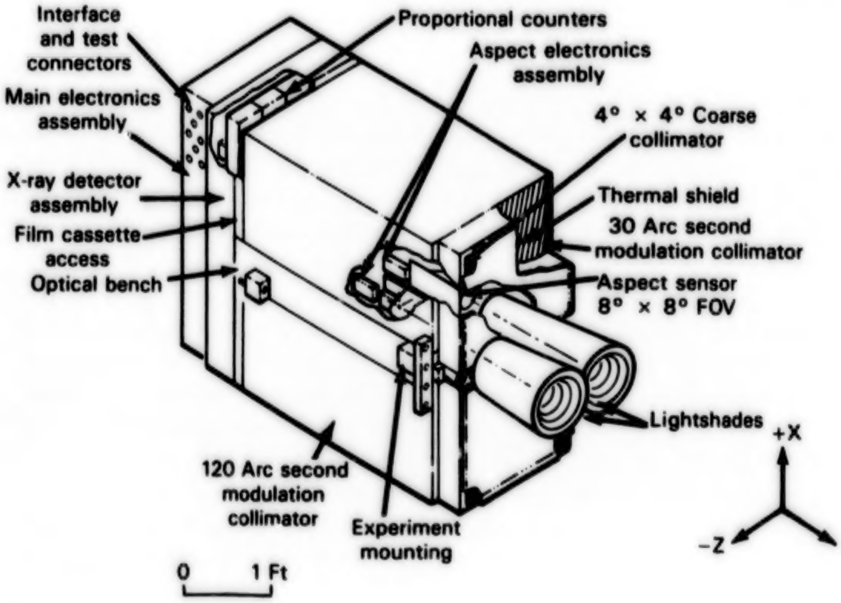


The Scanning Modulation Collimator, HEAO A-3. The A-3 experiment consisted of two scanning modulation collimators with proportional counters, aspect sensors, and electronics. The major purpose of this experiment was to determine accurately the position of selected cosmic X-ray sources and to investigate their size and structure. Principal Investigators were Herbert Gursky and Daniel Schwartz of the Smithsonian Astrophysical Observatory and Hale Bradt of MIT. Hardware was provided by American Science and Engineering, Inc.


Interface and test connectors
Main electronics assembly
X-ray detector assembly
Film cassette access
Optical bench
Proportional counters
Aspect electronics assembly
4° × 4° Coarse collimator
Thermal shield
30 Arc second modulation collimator
Aspect sensor 8° × 8° FOV
Lightshades
+X
–Z
+Y
120 Arc second modulation collimator
Experiment mounting
0
1 Ft

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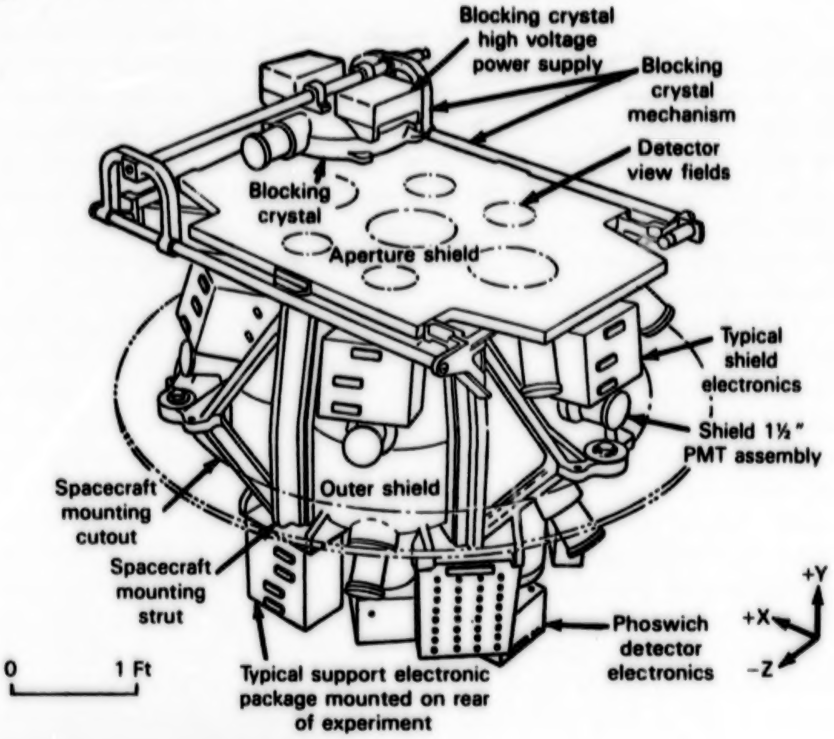
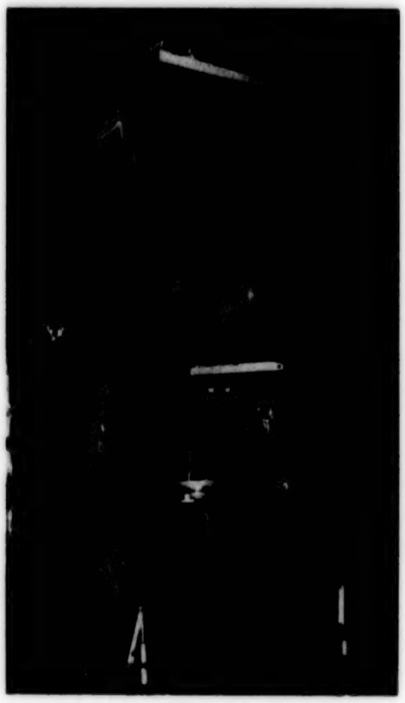

Blocking crystal high voltage power supply
Blocking crystal mechanism
Detector view fields
Blocking crystal
Aperture shield
Typical shield electronics
Shield 1½" PMT assembly
Spacecraft mounting cutout
Outer shield
Spacecraft mounting strut
+Y
+X
-Z
Phoswich detector electronics
0
1 Ft
Typical support electronic package mounted on rear of experiment



Hard X-ray and Low Energy Gamma Ray Experiment, HEAO A-4. The A-4 experiment consisted of a modular array of phoswich scintillator detectors, particle monitors, a digital processor containing power conditioning, and data handling electronics. The purpose of the experiment was to determine the position, spectrum, time variations, intensity, and other properties of selected X- and gamma ray sources in the energy range of 10 to 10 000 kiloelectron volts. Principal Investigators were Laurence Peterson of the University of California at San Diego (UCSD) and Walter Lewin of MIT. Experiment hardware was provided by UCSD and Time Zero Laboratories of Ball Brothers Research Corporation.

Everyone in the program had the same goal: to put three observatories in orbit that could fulfill the scientific objectives as stated in the proposal and to do it within cost and schedule. However, given the austere budget and the ambitious scientific objectives, it is fairly certain that this goal would not have been achieved if each group had not become strong advocates of its own particular viewpoint and responsibility. This understandably led to conflicts between one group of scientists and another, between scientists and subcontractors, between NASA and subcontractors, and between scientists and NASA.

The focal point of much of this conflict was Marshall Space Flight Center. Marshall was the NASA center with responsibility for HEAO. The program manager at Marshall was Fred Speer, a man with very definite ideas as to how the project should be managed. Many scientists, used to the informal style of small projects involving the flight of a balloon or a sounding rocket, were unprepared for Speer's highly formal style, developed during his experience with the Apollo manned space program. Halpern, always short of money, directed Speer to build the large, complex HEAO instruments just once and then to solve whatever problems that might develop, rather than to build two or three versions of them. Basically, the idea was that the engineering model, the prototype, and the flight unit would all be rolled into one. This concept was called "protoflight" (prototype + flight). It resulted in a great cost savings and a great increase in the pressure to get everything done right the first time and to stay on a strict schedule.

Most of the scientists, though not thrilled with the idea of having to build an entirely new type of instrument so that it worked correctly the first time it was tried, agreed that the protoflight approach was probably a necessity of life, given the limited budget. However, they did not view the documentation required by Marshall in the same light. "I hated the interminable paperwork," one scientist complained. Still another scientist said, "If we would've done everything that they asked us, the thing would still not be in orbit." Still others sought solace in humor. Bob Farnsworth, an engineer at the University of California at San Diego, used to cheer himself up when he was buried in documentation requirements by remembering the advice of his colleague Mike Pelling. "Well, when it's all over with," Pelling said, "just think how much better off they'll be." Tom Parnell, who had been through it all before in his years at Marshall, admitted, "It is a real shock to people who haven't been through it. We must prethink everything in nagging detail, everything that could go wrong and prepare for it. Also we have to worry about cost. The paperwork raises the cost, but it guarantees that, when we launch, everything we can do to ensure success is done."

Another objection heard more than once was that Marshall was too arbitrary in both a technical and monetary sense, so that minor changes in the

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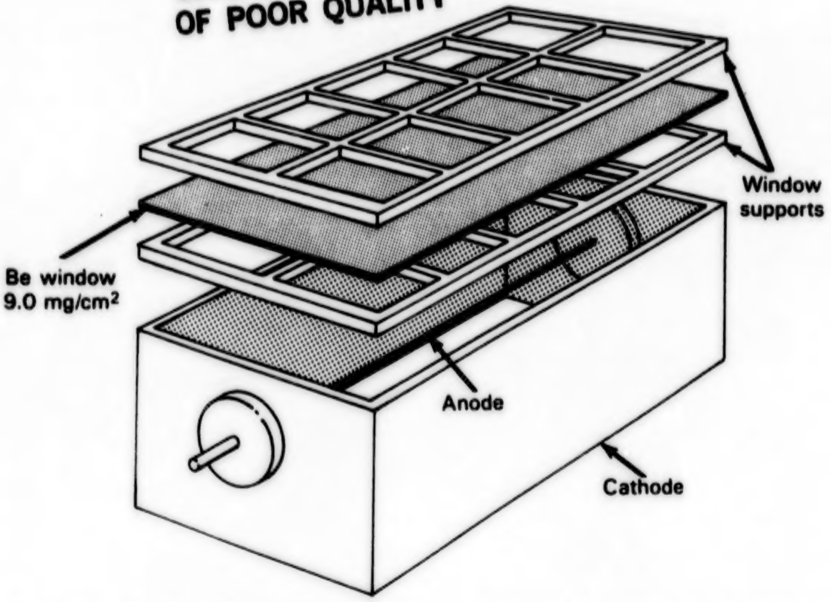

Schematic of a thin window gas proportional counter. The beryllium window is cemented between a supporting "sandwich," which in turn is hermetically sealed to the cathode to preserve the gas integrity. An X-ray photon entering the counter produces a cloud of electron-ion pairs in the gas. The electrons drift to the anode, producing an electric signal.

original plans were for the most part not allowed, even though they might have resulted in an overall cost savings, because they would have made the analysis of the data easier. This frustration led in at least one case to sub rosa techniques. Elihu Boldt wanted to add a provision for checking for bit errors in the data system of his instrument. (A bit error is an error that occurs in the transmission of data from one location to another, in this case from the spacecraft to the ground.) Engineers at Marshall assured him that the telemetry system was so good that the number of bit errors would be so low that there was no need to check for them. "But bit errors tend to occur in bursts and look remarkably like the data we get from some of the more interesting X-ray sources. We had to have a way to tell whether we were seeing a bit error or an X-ray burst, but they wouldn't allow it. So we put it in under another name. We called it a 'block encoder,' and they accepted it."

On the other hand, the relations between the scientists were not always a bed of roses either. "I found the negotiations within the consortium of scientists much more difficult than with Marshall," one scientist remarked. "They were draining, not so much because of the personalities involved, but because the problems were real, and they were all very dedicated to their own ideas and very capable of defending their own turf." On balance,

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Gordon Garmire

Stuart Bowyer

Claude Canizares
(Photo by Karen Tucker)

Robert Novick

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Left to right: George Clark, Roger Doxsey, and Hale Bradt. (Photo by Karen Tucker)

Dan Schwartz and Leon Van Speybroeck. (Photo by Karen Tucker)

though, most scientists were pleasantly surprised at how well they could work with colleagues who had often been on opposite sides of spirited rivalries, and many cited the interaction with other scientists and engineers as one of the high points of the project. They were not without kind words for the people at Marshall. Leon Van Speybroeck and others singled out Jim Power, a Marshall manager/engineer who was killed in an airplane crash while on HEAO business. "Jim was a very positive influence on the program. He genuinely tried to support the science and to use the resources at hand wisely." Hans Fichtner was praised by Hale Bradt and others as a "very enlightened engineer." And everyone seemed to agree that Carroll Dailey and Joseph B. Jones had a lot to do with the success of HEAO.

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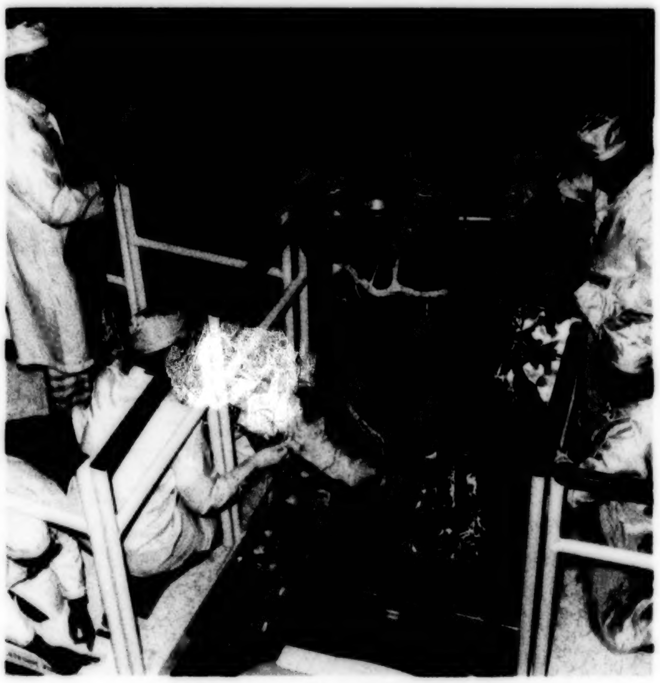
"They had fantastic sympathy for the experimenters," recalled Jim Matteson. Fred Speer, when looking back over the experience, said, "I hated to lose all the good people associated with the team. It was a sad moment to see them leave." He also praised the "overall team spirit that motivated the entire HEAO team" as an important factor in the success of the program. "This was accomplished by complete and open communications."

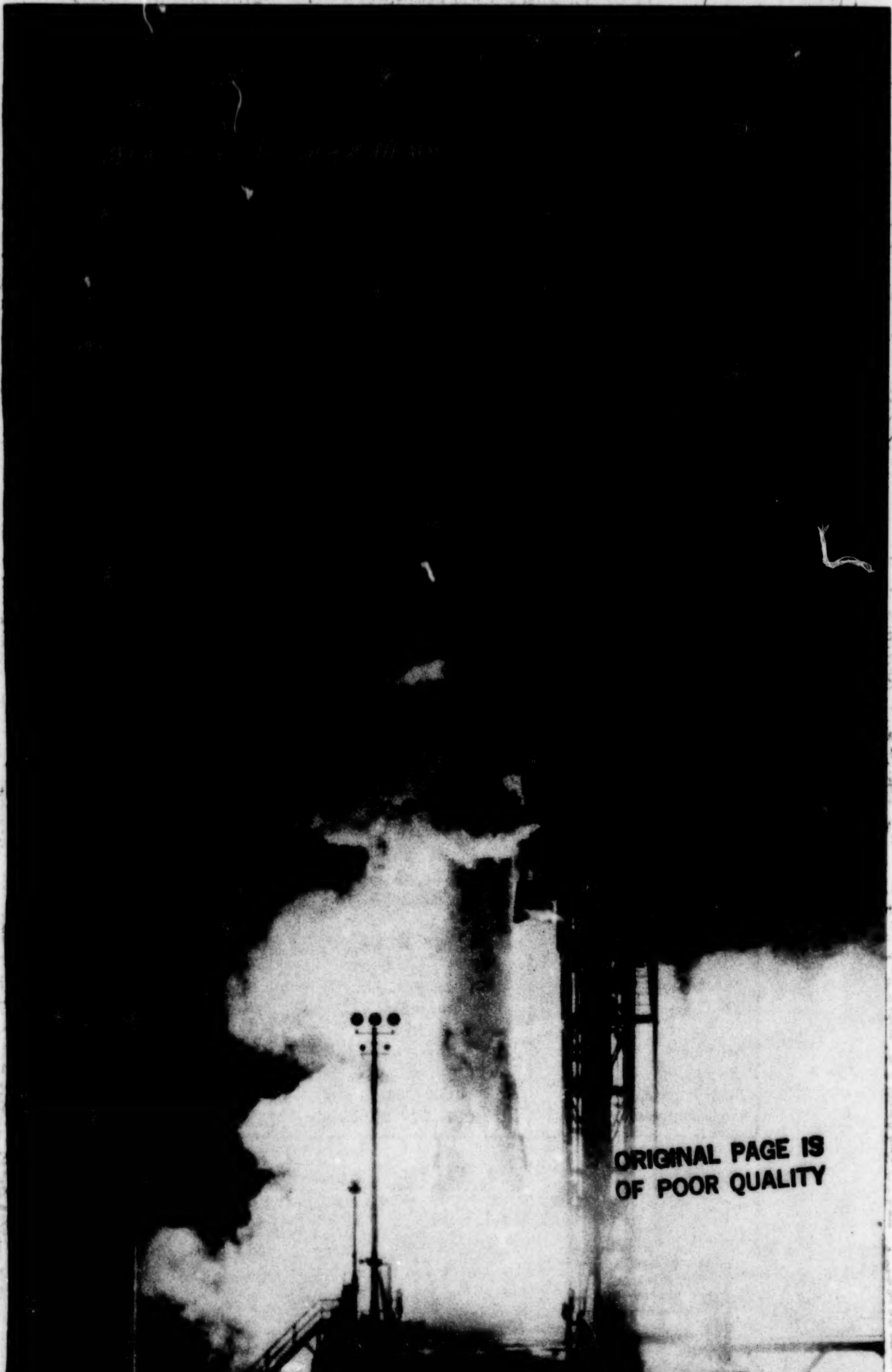
How did the scientists feel about Fred Speer once it was all over? "Fred Speer was a very excellent manager," said Frank McDonald, the HEAO 1 project scientist. Others were more reserved, but admitted that he earned their respect. "Fred Speer took his part of the world and made it work differently," said Ray Jorgensen, technical manager for the HEAO 3 gamma ray spectrometer at the Jet Propulsion Laboratory in Pasadena, California. "Although the management was way too much in the Apollo style," said Walter Lewin, "Speer deserves quite a bit of credit for some major decisions, particularly with respect to the gyros."

The gyros, or gyroscopes, were responsible for the only schedule slippage on HEAO 1. Gyroscopes are used in spacecraft to sense the rotation rates of the spacecraft. Through electronic controls, they provide data on the motion of the spacecraft. These data may be processed by an on-board computer to derive vehicle control corrections or be telemetered to the

Jim Matteson (center) and colleagues check out the HEAO A-4 experiment.



Laurence Peterson



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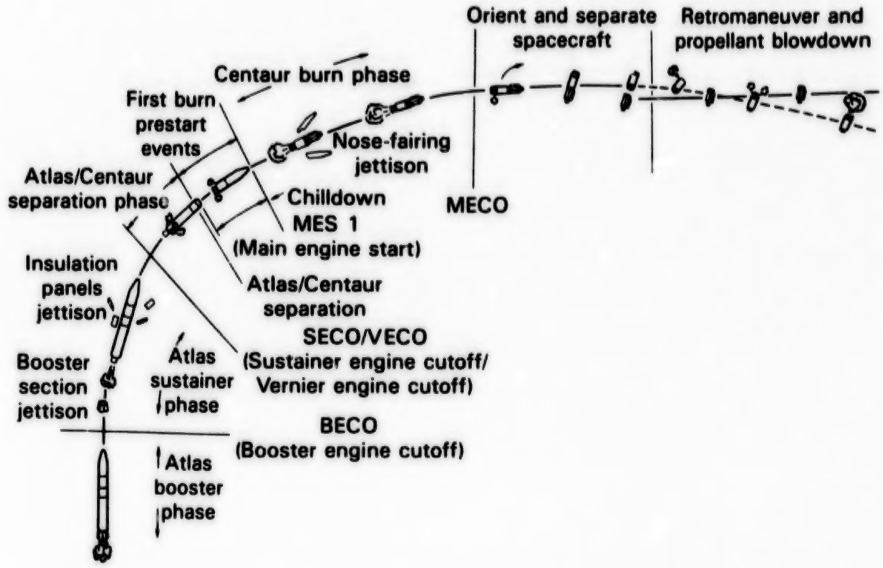
Orient and separate spacecraft
Retromaneuver and propellant blowdown
Centaur burn phase
First burn prestart events
Nose-fairing jettison
Atlas/Centaur separation phase
Chilldown
MES 1
(Main engine start)
MECO
Insulation panels jettison
Atlas/Centaur separation
SECO/VECO
(Sustainer engine cutoff/ Vernier engine cutoff)
Booster section jettison
Atlas sustainer phase
BECO
(Booster engine cutoff)
Atlas booster phase

Event	Basis	Approx. time from liftoff (sec.)
Liftoff	2-in. Motion	0
Roll program	Liftoff + 2 sec.	2-15
BECO	5.49 g	140
Booster package jettison	BECO + 3.1 sec.	143
Jettison insulation panels	BECO + 45 sec.	185
SECO	Prop. depletion	251
Separation	SECO + 1.9 sec.	253
MES 1	SECO + 11.5 sec.	263
Jettison nose fairing	MES 1 + 12 sec.	275
MECO 1	Parking orbit (guid.)	707
Separation	MECO + 665 sec.	1372
Start Retromaneuver	MECO 1 + 675 sec.	1382
Propellant blowdown start	MECO 1 + 3750 sec.	4397

Atlas-Centaur ascent profile.

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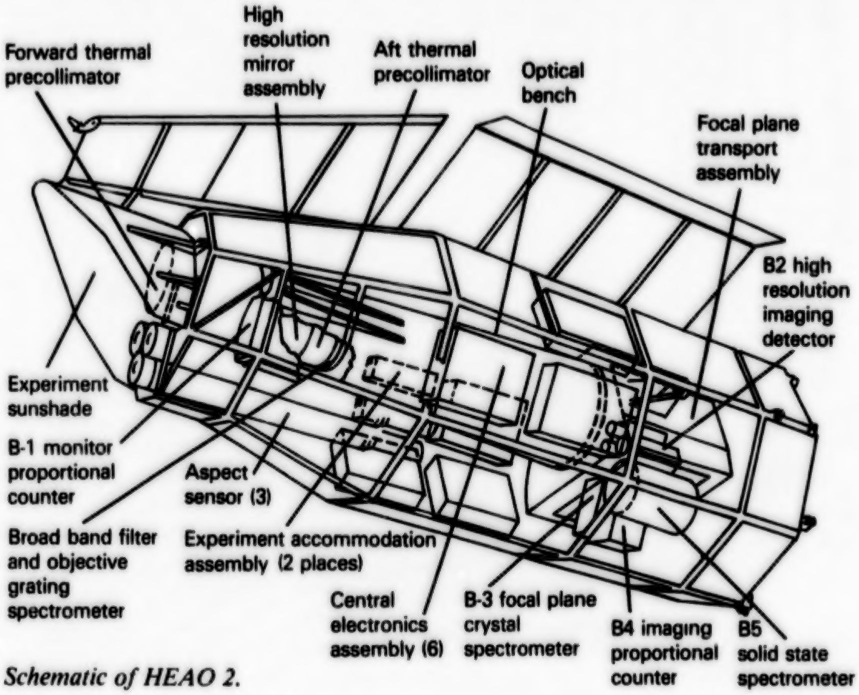
ground to provide detailed information about the motion of the spacecraft. Only a few months before the launch of HEAO 1, the gyros began to act up. They would short out in vacuum, or they would give erroneous readings. Over a period of six weeks, more than thirty such glitches occurred. There was no alternative but to postpone the launch until the gyro problem could be solved. Weeks and then months went by, and still the problem persisted. The scientists, knowing Speer's dedication to keeping on schedule, began to worry that he would launch the spacecraft anyway, knowing that it would last only six months, the minimum time for the mission to be considered a success. "Our concern was very misplaced," said Jim Matteson. "We learned that the problem was handled very effectively." Fred Wotjalik and other engineers worked overtime, making extra tests to reassure themselves that the gyros would work once the spacecraft was launched. Still, no one knew for sure what had caused the original problems, so they did not know for sure whether they would recur in orbit. A decision had to be made as to whether to keep fixing the gyros or to fly them. Halpern and Speer decided to fly them. "The gyro testing was agonizing," Herb Friedman remembered. "When we finally went, Dick Halpern told me it was OK. But I thought it was still a gamble."

The launch is always the most tense time of any space project, because if anything goes wrong then, it's all over. There could be no "soft failure" because there was no backup spacecraft. Everyone tries to stay calm, but no one succeeds. Even a veteran such as Fred Speer finds the countdown


Forward thermal precollimator
High resolution mirror assembly
Aft thermal precollimator
Optical bench
Focal plane transport assembly
B2 high resolution imaging detector
Experiment sunshade
B-1 monitor proportional counter
Aspect sensor (3)
Broad band filter and objective grating spectrometer
Experiment accommodation assembly (2 places)
Central electronics assembly (6)
B-3 focal plane crystal spectrometer
B4 imaging proportional counter
B5 solid state spectrometer

Schematic of HEAO 2.

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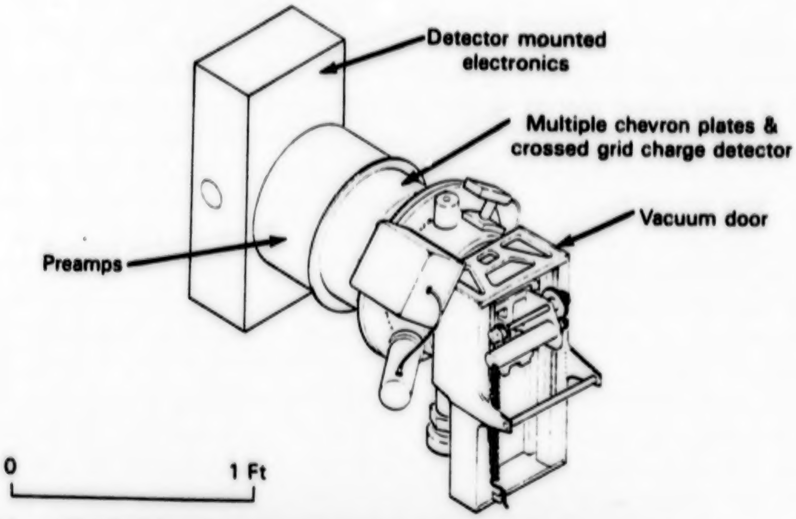
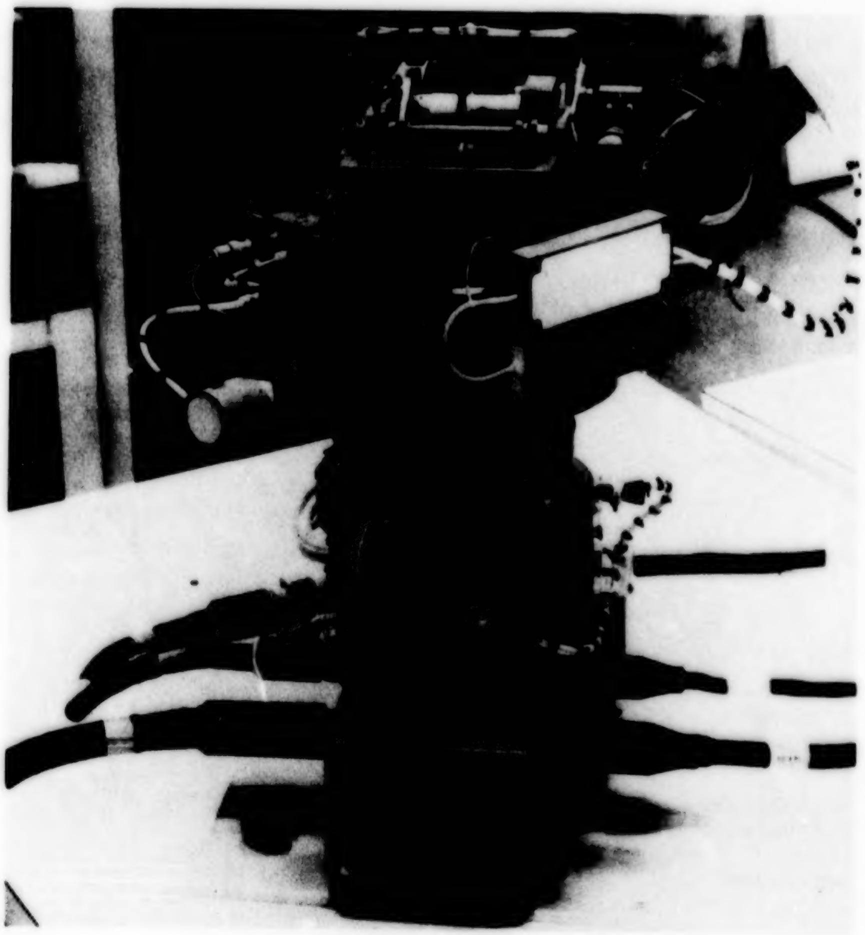

Detector mounted electronics
Multiple chevron plates & crossed grid charge detector
Vacuum door
Preamps
0
1 Ft



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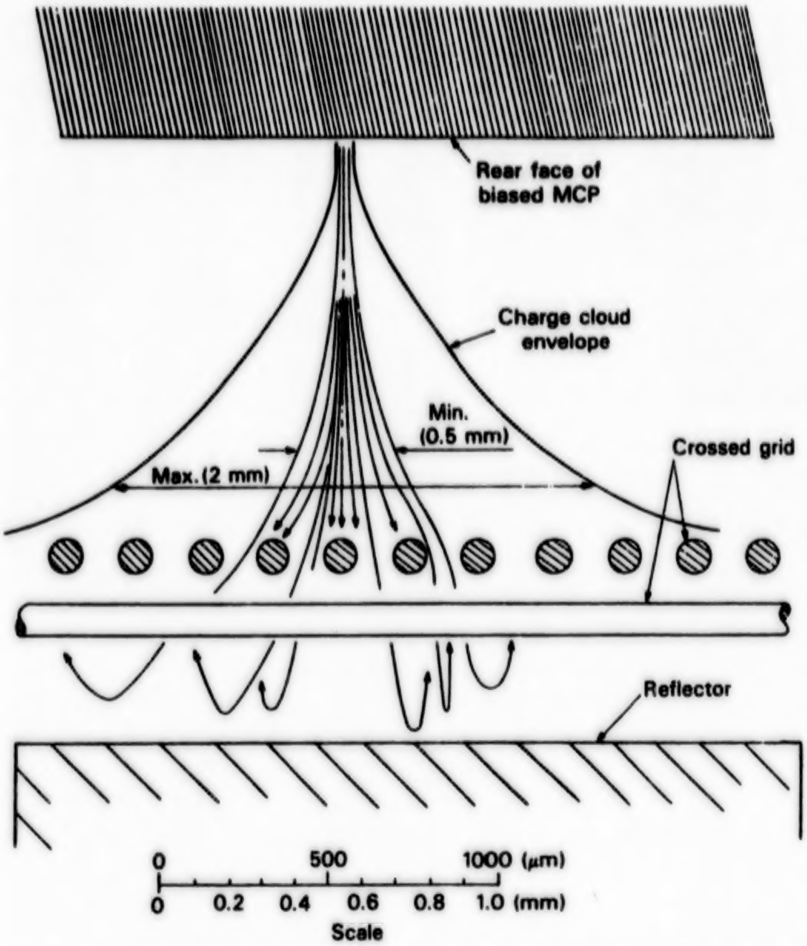
Rear face of biased MCP
Charge cloud envelope
Min. (0.5 mm)
Max. (2 mm)
Crossed grid
Reflector
0 500 1000 (μm)
0 0.2 0.4 0.6 0.8 1.0 (mm)
Scale

Operation of the High Resolution Imager. X-rays enter the microchannel plates shown at the top of the figure. The X-rays produce a cascade of photoelectrons that emerge from a few tubes at the surface. The electron charge cloud spreads over the criss-crossed grid of very fine wires. This grid of wires produces the electric signals that are decoded to give the position of the incoming X-ray.

← *The High Resolution Imager, HEAO B-2. Designed to use the imaging capability of the X-ray telescope, the High Resolution Imager used advanced solid-state techniques to record the images with a resolution of 1 to 2 arc seconds, the limit of the resolution capability of the telescope itself. The Principal Investigator was Riccardo Giacconi. Hardware was developed by American Science and Engineering.*

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Steve Murray demonstrates how the prototype of the High Resolution Imager was put together. (Photo by Karen Tucker)

Patrick Henry

"nervewracking." To Bob Farnsworth, it was "mindboggling. Seven or eight years of your life are sitting on top of a rocket." Hale Bradt was "impressed by how thin and fragile it looked." To Harvey Tananbaum, the scientific program manager of HEAO 2 from Harvard-Smithsonian, the rocket was "just beautiful," though he, too, found that it was "a frightening prospect to have millions of dollars and years of your life riding on the line." Jim Matteson's experience was typical. "I remember trying to rationalize away a disaster on the way down, saying to myself, 'well, if it blows up or doesn't go into orbit, I can live with it.' Thirty minutes before launch all this collapsed, and I realized that anything short of success would be an emotional disaster."

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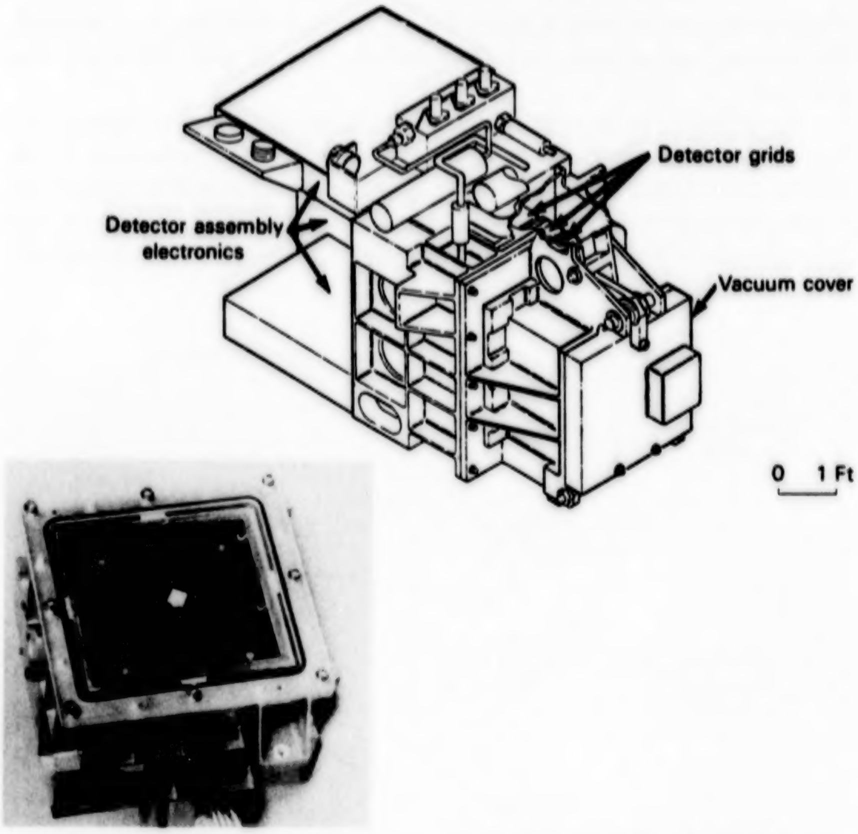

The Imaging Proportional Counter, HEAO B-4. The Imaging Proportional Counter used the same basic techniques as most of the X-ray detectors on HEAO 1, but the counter was electronically subdivided into very small regions so that each registered a small part of the X-ray image. The result was an image with a resolution of about 1 arc minute. What the Imaging Proportional Counter lacked in imaging resolution, it made up in greater field of view than the High Resolution Imager. The Principal Scientists were Herbert Gursky and Paul Gorenstein of Smithsonian Astrophysical Observatory. Hardware was developed by American Science and Engineering.

The night of the launch an electrical storm moved into the Cape Canaveral area, and the launch, scheduled shortly before midnight on August 11, 1977, was put off for an hour. The spacecraft computer went down, and a decision was made to load the program through Goddard, a very tricky maneuver. In the meantime, another complication had arisen. Several fishing boats were in the area where the rocket would be jettisoned after launch. Attempts to reach them by radio and get them to clear the area had failed. Helicopters were dispatched to drop messages on their decks. Because of the bad weather, the crews were below deck and did not respond. The launch was postponed another hour as the Launch Director waited for both the weather and the fishing boats to clear. Finally, Skip

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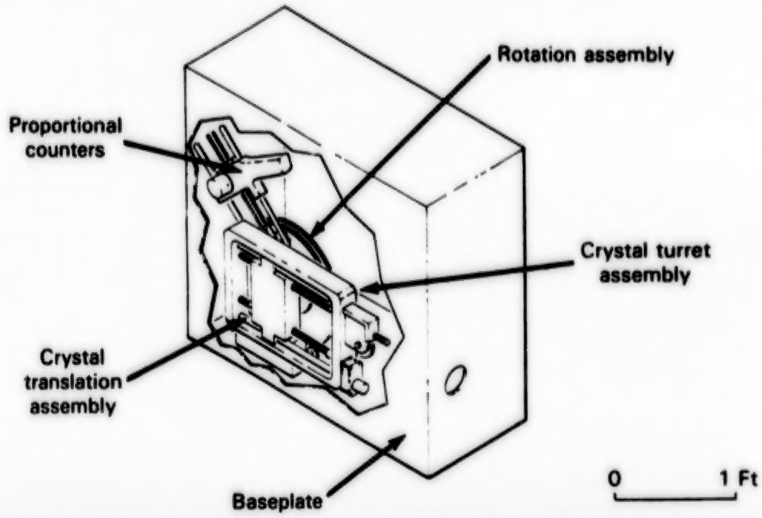
Mackey reached the fishing boats by a CB radio, and they turned south. The weather cooperated, too, and shortly after 2 a.m. HEAO 1 was launched.

For a little over two minutes the booster engines lifted the rocket away from Earth and into space. At 253 seconds after liftoff, separation of the booster engine from the main engine occurred. Ten seconds later the main engine started to burn. It burned for 434 seconds, taking the spacecraft over 200 miles above the surface of Earth. Almost 23 minutes after launch, the



The Focal Plane Crystal Spectrometer, HEAO B-3. The Focal Plane Crystal Spectrometer made use of the X-ray diffraction properties of certain crystals to study in detail the X-ray spectra produced by celestial targets. The detector for the diffracted rays was a small proportional counter. This instrument could detect individual X-ray emission lines to help unravel questions about the chemical composition and other properties of cosmic X-ray sources. The Principal Scientist was George Clark of MIT. Hardware was developed by MIT.

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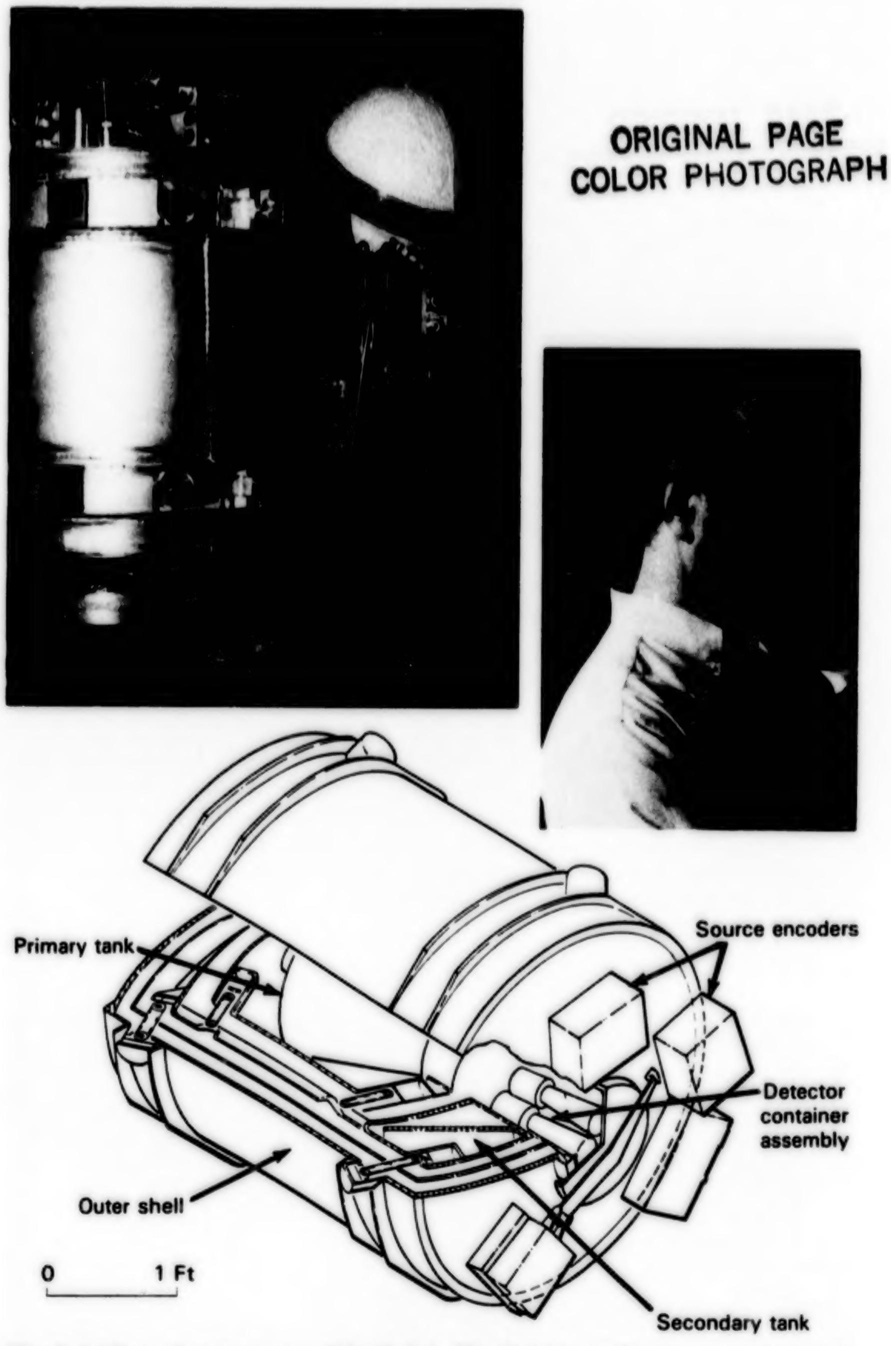
Primary tank
Source encoders
Detector container assembly
Outer shell
0
1 Ft
Secondary tank

The Solid State Spectrometer, HEAO B-5. The Solid State Spectrometer had to be cryogenically cooled with solid methane and ammonia for its silicon-germanium crystal to function properly. Its advantage was that it could observe the entire spectrum at once, measuring the energy of each photon hitting the crystal, whereas the Focal Plane Crystal Spectrometer could examine only a small band of energies at any one setting of the crystal turret. The two spectrometers complemented each other in sensitivity and energy resolution. The Principal Scientist was Elihu Boldt of Goddard Space Flight Center. Hardware was developed by Goddard under an intercenter agreement.

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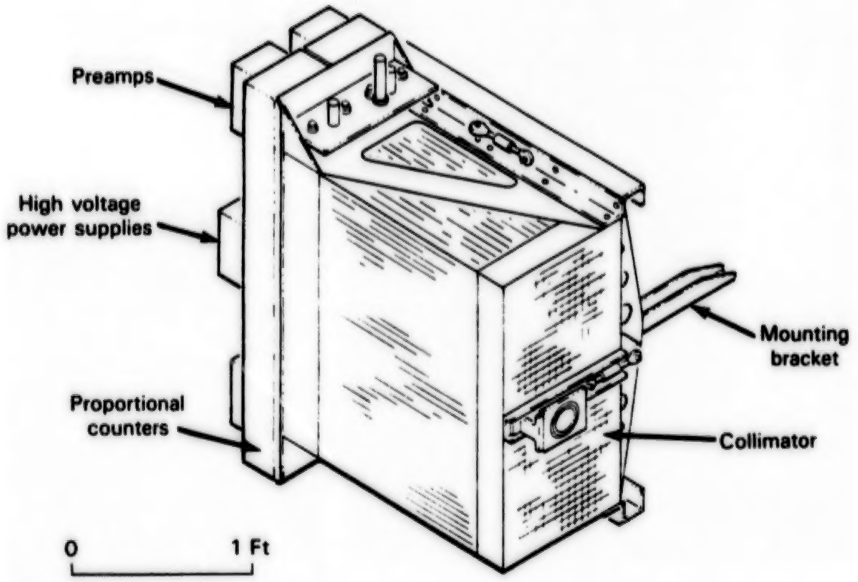
Preamps
High voltage power supplies
Proportional counters
Mounting bracket
Collimator
0
1 Ft

The Monitor Proportional Counter, HEAO B-1. The Monitor Proportional Counter was mounted near one end of the observatory and operated independently of the telescope. It observed the same region of sky as the telescope but over a much wider energy range. It provided a means of correlating observations made by all the focal plane instruments. The Principal Investigator was Riccardo Giacconi. Hardware was developed by American Science and Engineering.

Paul Gorenstein
(Photo by Karen Tucker)

Harvey Tananbaum
(Photo by Karen Tucker)

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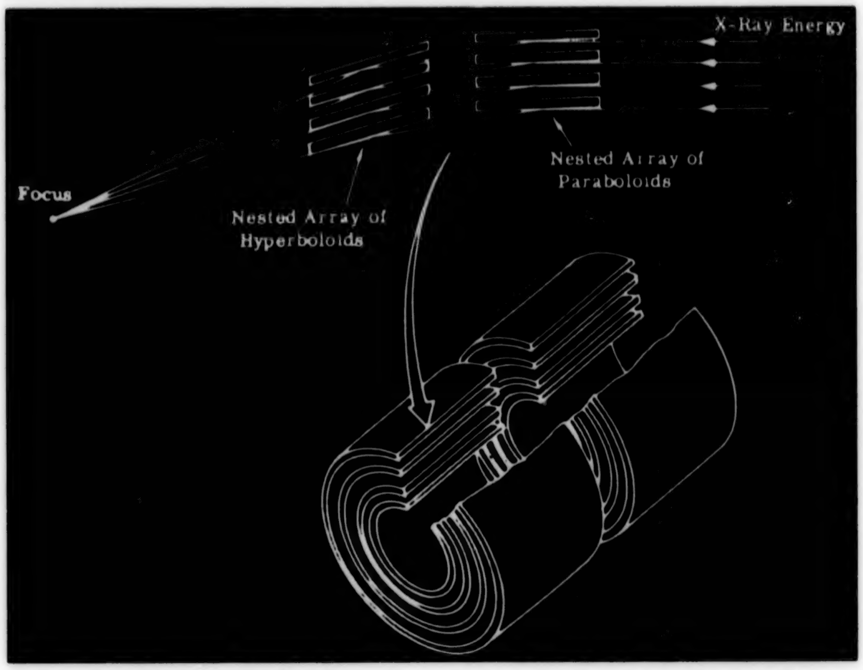
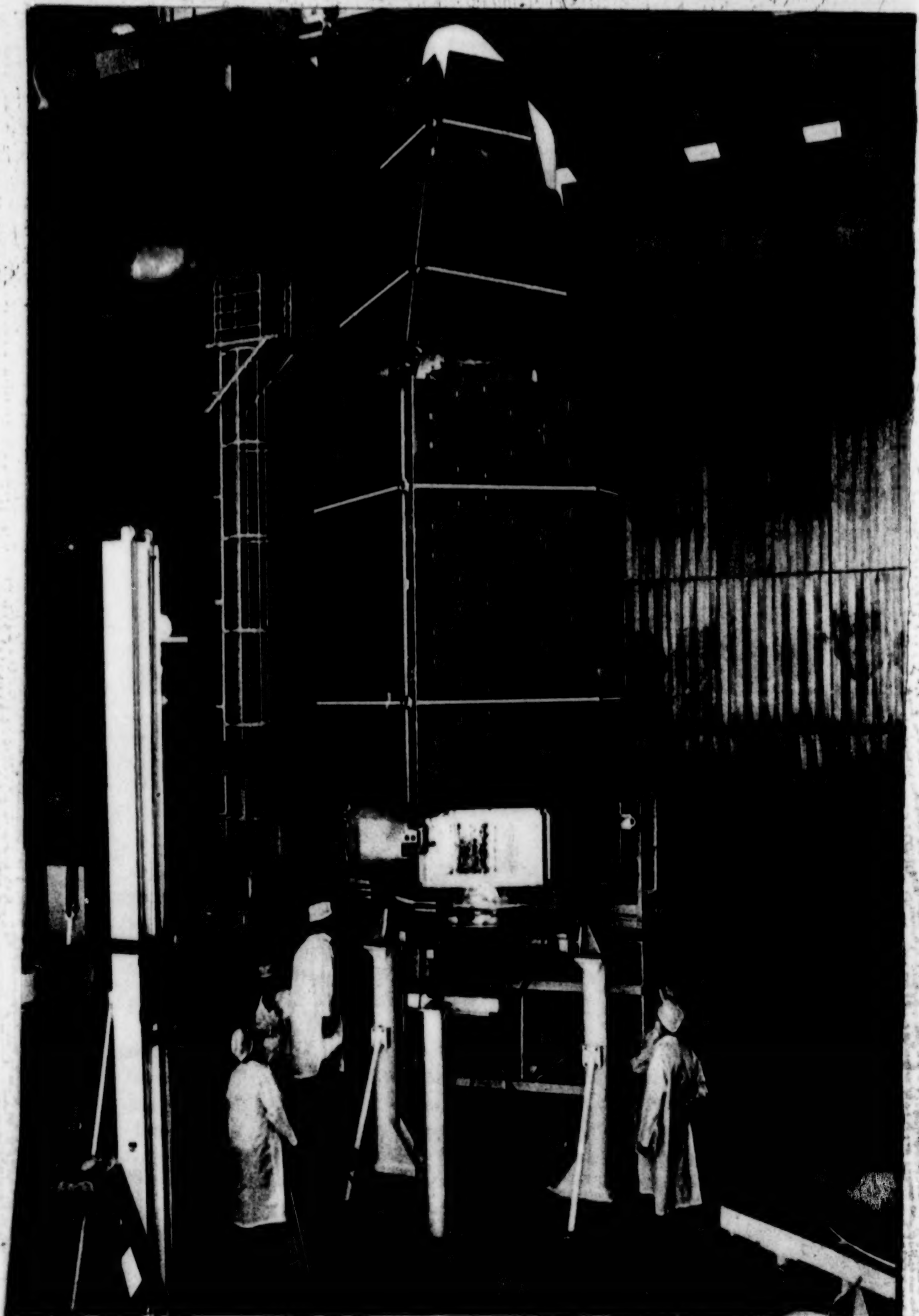


Schematic of the Grazing Incidence X-ray Telescope. X-rays entering the telescope strike the slightly curved mirrors at a grazing angle and are concentrated in the focal plane. The four concentric mirrors concentrated the flux of X-rays so that objects 1000 times fainter than ever detected before could be examined in detail. (Smithsonian Institution Photo No. 80-20240)

main engine separated from the spacecraft. HEAO 1 was in orbit. Dick Halpern and Fred Speer were the last to leave the Control Center. Heading toward town, they both felt so drained they decided to pass up the postlaunch celebration party. It had been a long road together. A few days later, the instruments were activated and began to return data. More than a decade after that first meeting at Woods Hole, the first HEAO was a reality.

Meanwhile, the HEAO 2 team was pushing to meet their launch deadline of November 1978, only 15 months away. HEAO 2 was quantitatively different from the other missions and from anything that had been tried before. In the understated words of Paul Gorenstein of Harvard-Smithsonian, "it was a somewhat audacious step, because no prototype for the instruments existed. But we were confident we could do it." The goal of the HEAO 2 team was nothing less than to put the young science of X-ray astronomy on a par with optical and radio astronomy. To do this, they planned to make an X-ray observatory that would detect sources a thousand times fainter than any previously observed. They hoped to accomplish this by flying a complex array of mirrors that would focus X-rays onto one of



The HEAO 2 X-ray mirror completely assembled for ground testing. (Photo courtesy Perkin-Elmer Corp.)

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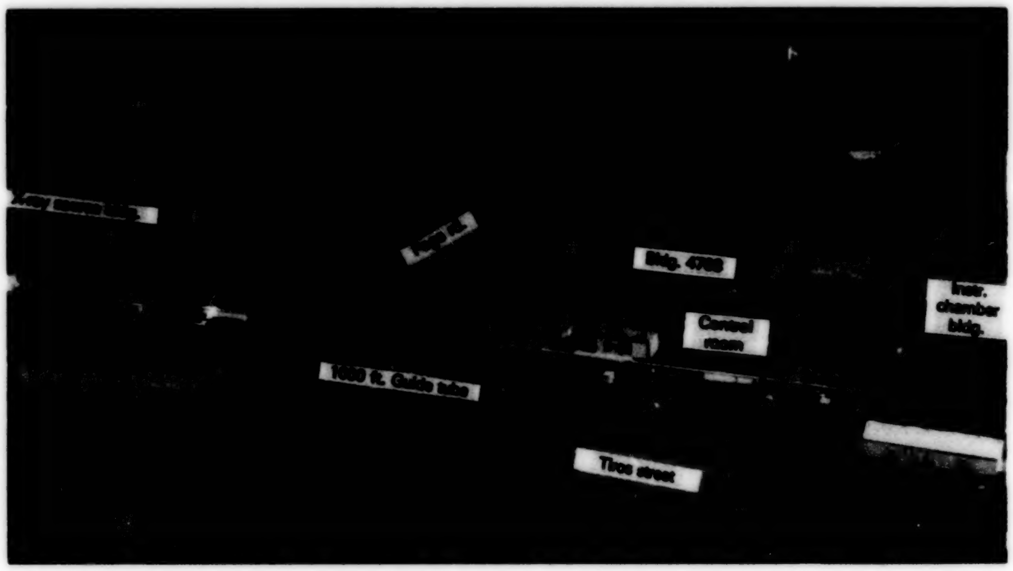
several sensitive X-ray detectors. Several detectors would be needed because it was not possible to build a single detector that could make fine images and detailed spectral measurements, see a large field of view, and detect very weak sources. The absence of a single detector with all desired properties meant that the scientists involved would have to work together closely to develop a complement of detectors capable of achieving the objectives of the observatory. A unified scientific approach would be necessary to deal with the many problems that would arise and the compromises and tradeoffs that would be necessary. Accordingly, from the very beginning, in the proposal stage, a consortium of experimenters was organized. The consortium included scientists from AS&E, Columbia University, Goddard Space Flight Center, MIT, and the Smithsonian Astrophysical Observatory, with Riccardo Giacconi of the Smithsonian as the Principal Investigator and Scientific Director of the observatory. The consortium scientists agreed that, in addition to obtaining data from the instruments for which their individual institutions had responsibility, all scientists would share in the data from all instruments.

The four focal plane detectors chosen were the High Resolution Imager, the Imaging Proportional Counter, the Solid State Spectrometer, and the Focal Plane Crystal Spectrometer. The High Resolution Imager offered the highest spatial resolution. However, it had no energy resolution, and its field of view was small. The Imaging Proportional Counter could detect weaker sources than the High Resolution Imager, had a wider field of view, could make "broad brush" images of sources, and had a modest degree of



The X-ray telescope calibration facility at Marshall Space Flight Center.

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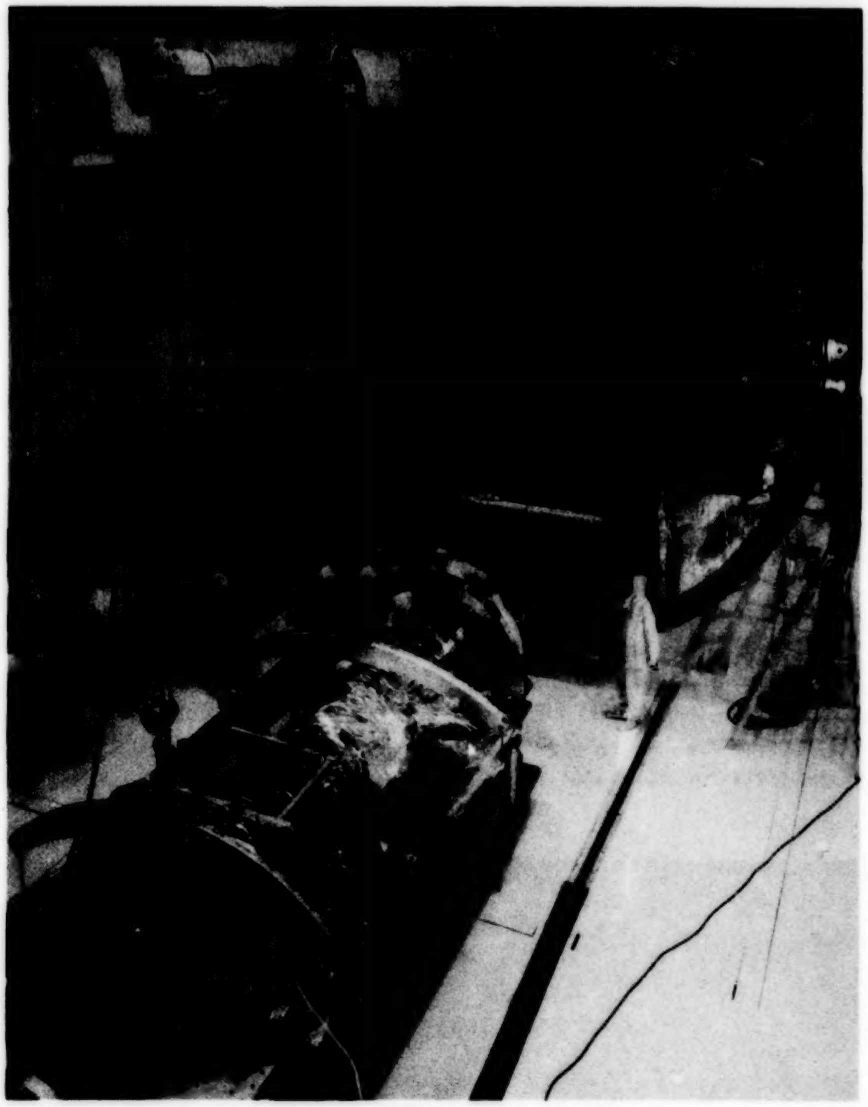

HEAO 2 is installed in calibration facility vacuum chamber.

energy resolution. This versatile instrument was the workhorse of the observatory and was the most used instrument. It was designed and developed by Paul Gorenstein and F.R. Harnden of the Smithsonian. The Solid State Spectrometer developed by Elihu Boldt, Stephen Holt, and Robert Becker could observe the entire spectrum at once, measuring the energy of each photon that hit the silicon germanium crystal at the heart of the detector. The Focal Plane Crystal Spectrometer developed by George Clark, Claude Canizares, and Tom Markert of MIT was used to study the details of the

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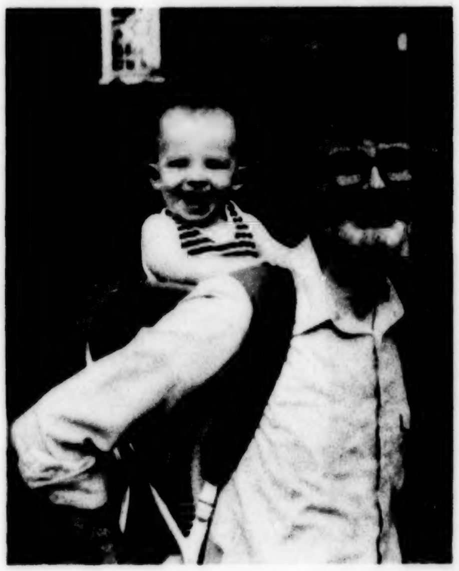
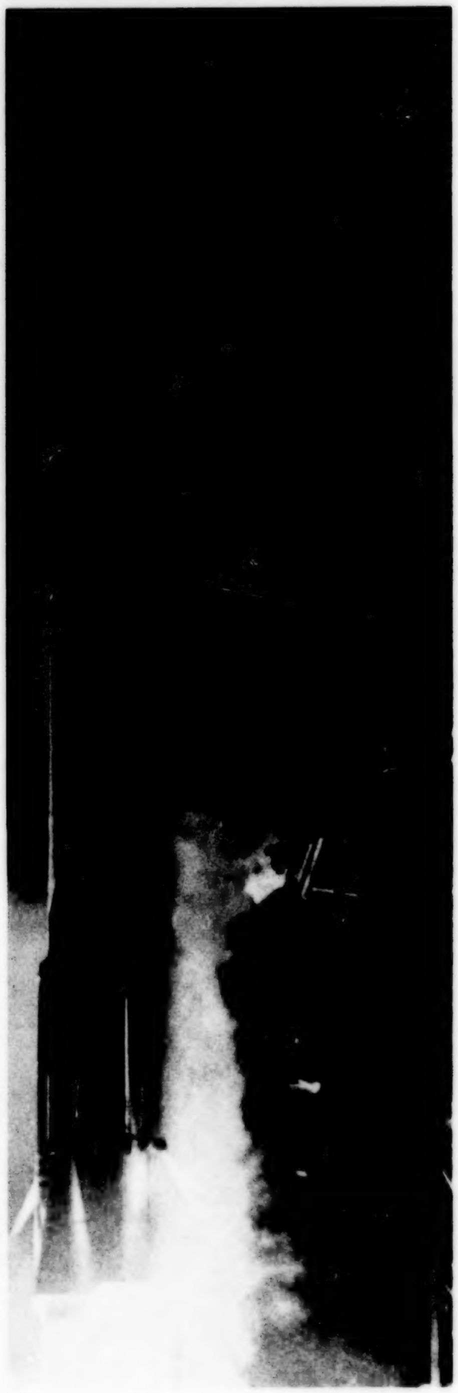


Fred Seward and son Robert (Photo by Susan Seward)

Ethan Schreier



November 13, 1978. The launch of HEAO 2.

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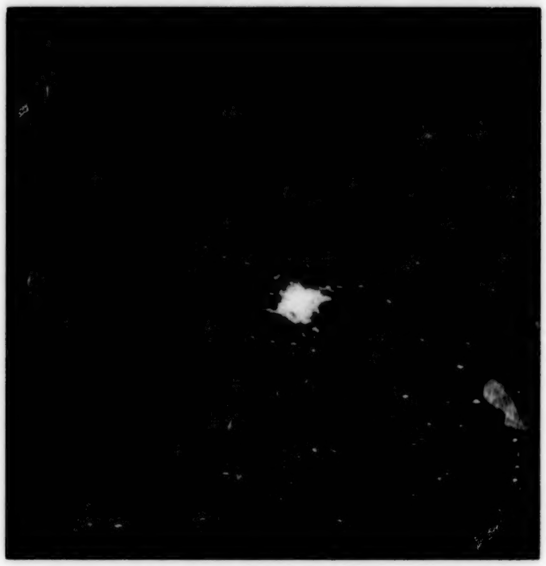
spectra in a narrow energy band for strong X-ray sources. Two other auxiliary instruments augmented the capabilities of the observatory. They were the Objective Grating Spectrometer, which for strong sources could be used with the High Resolution Imager to provide spectral information, and the Monitor Proportional Counter, which was situated outside the focal plane with a viewing direction parallel to the telescope axis and served as a continuous monitor on the sources viewed by the telescope. The Columbia



First light of HEAO 2, now nicknamed the Einstein Observatory: the black hole candidate, Cygnus X-1.

Einstein "first light" party at the Harvard-Smithsonian Center for Astrophysics. Left to right: Leon Van Speybroeck, Kenton Evans, Martin Elvis, Pepi Fabbiano, Arnold Epstein, Graziella Branduardi-Raymont, Mirella Giacconi, and Riccardo Giacconi. (Photo by Fred Seward)

University group consisting of Robert Novick, Knox Long, William Ku, and David Helfand participated in all scientific aspects of the mission. Ethan Schreier of the Smithsonian directed the mission operation planning and implementation. Ted Kirchner of AS&E was the program manager for the experiment during the early design and development phase. When the experiment entered the manufacturing phase, Bruce Dias became program manager and was responsible for directing the manufacture, assembly, integration, and testing of the experiment.

The Solid State Spectrometer had to be cooled with solid methane and ammonia to a temperature of about 100 K (– 280° F) in order to work properly. This requirement created difficult design problems. Steve Holt recalled some of those problems. "There was a chance that the vent lines could clog with ice and explode. We had to prove that it would rupture internally first. Riccardo felt that he was flying a bomb on the observatory. Every place we took it, to American Science and Engineering, to TRW and then to the Cape, it had to be monitored 24 hours a day." No serious mishaps occurred, but even so, there was a constant worry that something would go wrong. Water vapor from the insulation material would accumulate on the detector and freeze into a thin layer of ice. Periodic defrosting of the detector by heating it to 220 K (– 63° F) removed the ice layer. The defrosts were never routine, however. "We would go into focus once every two weeks and would start to defrost 12 hours before," Holt said. "We would be terrified each time that the command system wouldn't work and would have to wait until the next pass over the ground station to see if it had worked, or whether we had a bomb, a complete failure." The system always worked, though, and got better as time went on.

The High Resolution Imager presented problems of a different type. Unlike the other instruments, which were adaptations of devices that had operated in other applications, there was no previously existing prototype. Steve Murray, Patrick Henry, Edwin Kellogg, Harvey Tananbaum, and Leon Van Speybroeck, all of Smithsonian Astrophysical Observatory, developed the instrument. The first few tries did not work. Finally, Murray came across an article by a group of scientists at the University of Leicester in Great Britain. The article described a type of detector that looked promising. Two of these scientists, Kenton Evans and Ken Pounds, brought a prototype unit. It was set up and tested. It did not work. Evans and Pounds said that the unit worked at home. Finally, the problem was traced to an inadequate approximation in the computer program that was used to process the results and to vacuum pumps that were putting noise into the system. The Smithsonian group then set up a laboratory and built a high resolution X-ray camera based on the principles of the British instrument. In the words of Steve Murray, "We just kept trying things until something worked. We really played the basement inventors. It took a few years, but after going down many blind alleys, finally we succeeded. In the end it turned out that the simplest ways were the ways that worked.'' For example, the detector

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required a grid of wires that had to be wound 128 wires to the inch, evenly spaced. How to space them evenly? Wind a double strand of wire and then unwind one strand.

The next step was to test the High Resolution Imager on a rocket flight. This led to a spectacular series of rocket failures unrelated to the quality of the detector. On one flight a relay failed; on another the doors did not open; on yet another a switch did not work. Finally, in July 1978, only a few months before launch, they had the one and only successful flight test of the detector.

The heart of the observatory was the mirror assembly. Leon Van Speybroeck of the Smithsonian Astrophysical Observatory assumed primary responsibility for the development of the mirror assembly. Because of their short wavelength and high energy, X-rays encountering a mirror or lens at a large angle would not be reflected but would slam into the surface and be absorbed, in much the same way as a stream of bullets encountering a wooden wall. However, just as bullets hitting the wall at a grazing angle would ricochet, so too can X-rays impinging at grazing angles on polished glass mirror surfaces be reflected with high efficiency to form an image. These X-rays are recorded on one of the detectors at the focus of the telescope and converted to electric signals that are recorded on magnetic tape and transmitted to Earth when the observatory passes over one of the ground stations.

At the Einstein Observatory Data Center at the Harvard-Smithsonian Center for Astrophysics, Rick Harnden studies the X-ray image of the Crab Nebula, the remnant of an exploding star. (Photo by Dane Penland; Smithsonian Institution Photo No. 80-16232)

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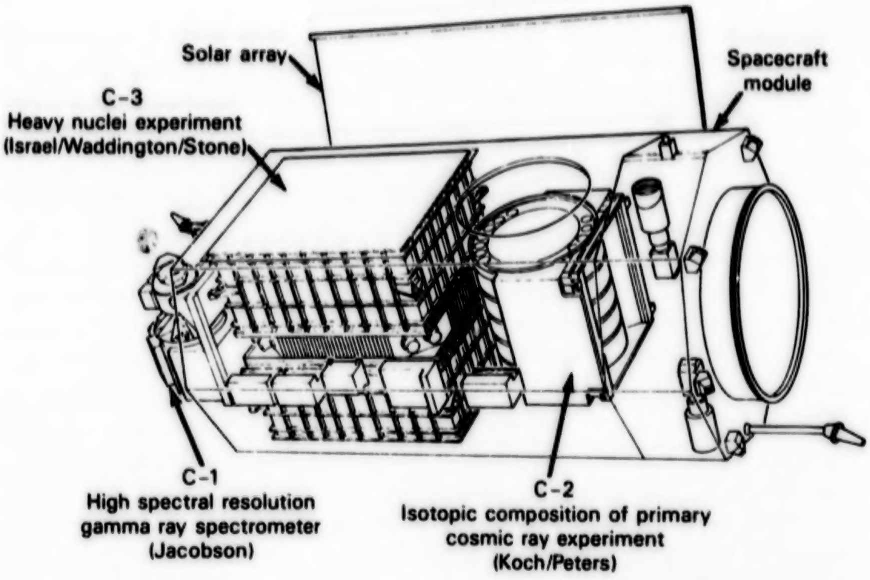
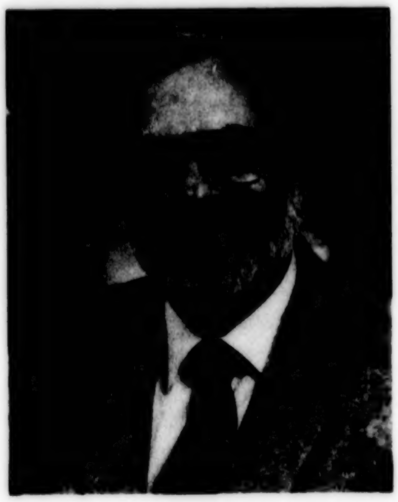

Solar array
Spacecraft module
C-3
Heavy nuclei experiment
(Israel/Waddington/Stone)
C-1
High spectral resolution
gamma ray spectrometer
(Jacobson)
C-2
Isotopic composition of primary
cosmic ray experiment
(Koch/Peters)

Schematic of HEAO 3.



Allan Jacobson

The mirrors were made at Perkin-Elmer Corporation by a team headed by P. Young. First, the mirror elements were diamond ground to approximate shape. Then they were polished, coated with chromium and nickel, aligned, and bonded to a support structure. This was no trivial problem. The mirror elements, which weighed a few thousand pounds, had to be supported in such a way as to mimic the gravity-free state of orbit. The Perkin-Elmer engineers, together with Gerry Austin and William Antrim of AS&E, developed a scheme of 32 counterweights placed so that the mirrors essentially floated and assumed their unconstrained, gravity-free state.

The difference in the way that X-rays are reflected means the design of the X-ray telescope must be different from an optical telescope, which uses flat dishes to reflect light. Instead, the X-ray telescope used an array of four nested glass tubes. The surfaces of these mirrors had to be polished internally, a technically much more difficult task than polishing conventional telescope mirrors. Even more worrisome was the lack of a conventional method to measure the smoothness of the surface. No rough spots on the surface greater than about 30 angstroms, that is, about one ten-millionth of an inch, could be tolerated. Getting the smoothest possible surface was critical, because if the surface is rough, it scatters the radiation and smears the image. The smoothness of conventional mirrors could be measured by studying the interference of light waves scattering off the mirror. This was not possible for the nested X-ray mirrors. The solution was to put a piece of transparent plastic tape on the mirrors, make an impression, and then run the tape through the interference machine.

Another problem was to measure the roundness of the mirrors. The mirrors were very flexible and would deform under their own weight. A small speck of dust on the measuring table would cause the measure of the roundness of the mirrors to vary from time to time. Finally, Van Speybroeck came up with a solution: float the mirrors in a vat of mercury during the measuring process. NASA was skeptical, so Van Speybroeck found a quantity of mercury left over from a colleague's experiment and demonstrated the feasibility of his idea with a prototype, after which NASA agreed to do it with the Einstein Observatory mirrors.

Finally, the mirror assembly and the detectors had to be integrated into a single observatory and tested. This testing took place late in the summer of 1977. A calibration facility had been built at Marshall Space Flight Center especially for testing the Einstein Observatory. This facility included vacuum pumps, a 1000-foot-long pipe to provide the separation between source and telescope that was needed to permit effective focusing, a vacuum chamber to house the observatory, and an adjustable source of X-rays to direct onto the telescope. Originally, six months had been allotted for testing of the observatory, but because of a six-month slip in schedule, NASA shortened the testing period to one month. Giacconi protested. One month was simply not enough time to make the more than a thousand separate measurements that were needed to make sure the observatory would work in orbit. But one month is all they would get, so they came up with an alternative plan. They would work 24 hours a day, in two overlapping 13-hour shifts. To ensure that the work was done as efficiently as possible, Van Speybroeck developed a computer program to optimize the testing. A schedule of 1397 separate tests was developed, and time was set aside for reworking hardware problems and retesting. This reserve turned out to be very important, as several problems did arise, and potentially serious inflight problems were avoided.

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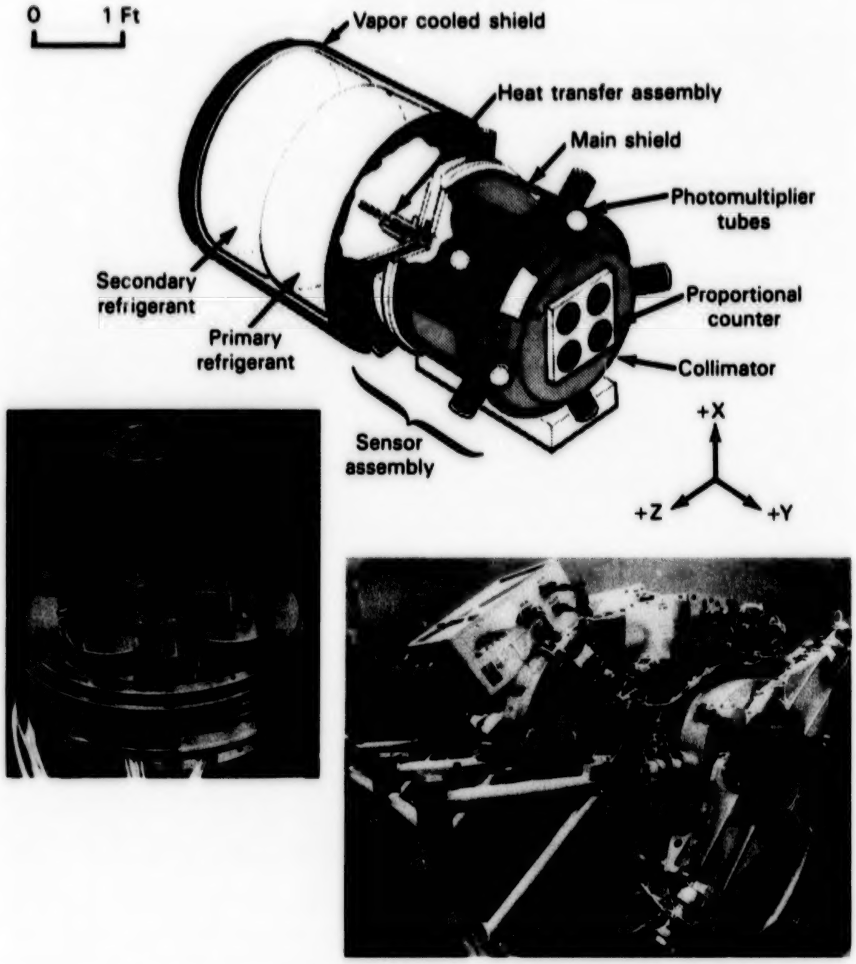
0
1 Ft
Vapor cooled shield
Heat transfer assembly
Main shield
Photomultiplier tubes
Secondary refrigerant
Primary refrigerant
Proportional counter
Collimator
Sensor assembly
+X
+Z
+Y

Gamma Ray Spectrometer, HEAO C-1. The Gamma Ray Spectrometer consisted of a cluster of four cooled, high-purity germanium detectors in a cesium-iodide sodium-activated shield. The germanium crystals are cooled by a solid cryogen refrigerator. The goal of the experiment was to explore for sources of X-ray and gamma ray line emissions. The instrument measured the spectrum and intensity of both diffuse and discrete sources of X- and gamma radiation. It also measured the isotropy of the diffuse background as well as time variations in the gamma ray flux from discrete sources. The Principal Investigator was Allan Jacobson of NASA's Jet Propulsion Laboratory in Pasadena, California.

An important by-product of the calibration of the observatory was the development of the computer software to analyze the large volume of data generated in the testing. This efficient data handling system was developed largely by Christine Jones, William Forman, Arnold Epstein, Jonathan Grindley, Jeffrey Morris, Schreier, and Van Speybroeck of the Smithsonian. It formed a basis for the data handling system used to reduce and

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Isotopic Composition of Primary Cosmic Rays Experiment, HEAO C-2. Flash tube arrays defined the trajectory of incident particles through the detectors, which were powder Cerenkov counters. The indices of refraction of the counters were chosen to maximize the useful observation time for the geomagnetic cutoff associated with the orbit of the observatory. This experiment measured the isotopic composition of primary cosmic rays with atomic charge z in the range of 4 (beryllium) to 56 (iron) and in the momentum range 2 to 20 billion electron volts per nucleon. In addition, the charge resolution of the instrument allowed identification of all incident nuclei up to charge $z = 50$ (tin). The Principal Investigators were Lydie Koch-Miramond of the Center for Nuclear Studies, Saclay, France, and B. Peters and I. Rasmussen of the Danish Space Research Institute, Copenhagen, Denmark.

analyze the data after the launching of the observatory. It is an efficient, thoroughly "de-bugged" system that allows one to go smoothly from observation to data analysis and is likely to be the prototype for future astronomical data handling systems.

The launch of HEAO 2 was scheduled for shortly after midnight on November 13, 1978. As usual, the scientists were skittish about readiness of the launch vehicle. The good track record of the Atlas-Centaur system was

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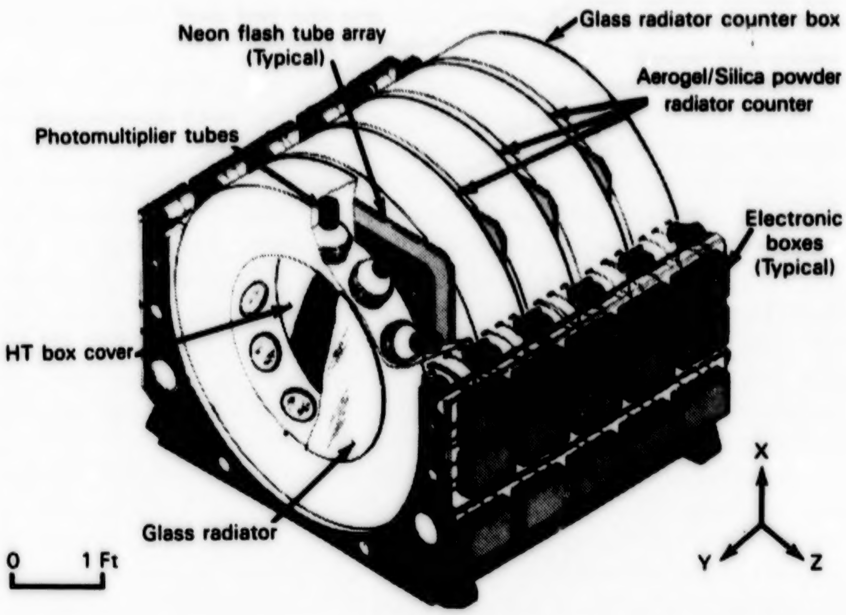

reassuring, to a point. "But we had only one instrument," Harvey Tananbaum said, "so there were no second opportunities. That launch vehicle didn't have to be good. It had to be perfect. I think they (the launch team) were a little miffed with the aggressiveness with which we were questioning them. I must say that everything did go smoothly, so I guess their reassurances were well founded. It was just that we had so much invested that we felt we had the right to know about every questionable area."

To protect this right, Giacconi sat in the control area with the NASA officials, so he would have final okay for the experiments in case questions arose about the vehicle or the conditions. Pat Henry, who had followed the experiment after calibration on through Marshall and integration with the spacecraft at TRW, was at Giacconi's side. The countdown moved forward without a hitch. At T minus 20 seconds, Henry gave up his seat in the control room and ran outside to see the launch. Harvey Tananbaum was watching from the bleachers. "I felt a chill run through my body when I saw the tower light up at T minus 1 with ignition. It was like lightning and thunder. You couldn't hear anything for several seconds. By then the vehicle had already lifted off. It began to rise very, very slowly, gathering speed. You momentarily forgot that it was carrying your life's work, as it were, under the nose cone."

A few minutes later the report came in that HEAO 2 had achieved orbit. Cries of jubilation. A sigh of relief from Fred Speer. And a deep sense of satisfaction for everyone involved. Almost immediately these feelings were replaced with nervous anticipation about activation of the instruments a few days later. In the words of Ethan Schreier, "everyone was completely wired. No one could sleep until we arrived at Goddard. For the next six days I must not have slept more than 15 or 20 hours."

The first step was to check the star trackers. Much to the horror of the scientists, they appeared to be malfunctioning. "We turned them off and sat there for four days, trying to figure out what was wrong," Schreier recalled. "Then we realized that the star trackers were picking up the reflection of the moon off the ocean, and that there was no problem." Then it seemed that the pointing system was not working. "We found very large drifts," Schreier said. "Everyone was going bananas." By studying the data, they concluded that the star trackers were off by a few percent. They consulted the manufacturers, who studied the data from the star trackers and confirmed that they were working perfectly. The effect was traced to a memorandum written years ago in which the number 32 767 had been approximated as 32 000 in a conversion formula.

Finally, four days after the launch, the spacecraft slewed to Cygnus X-1, a strong X-ray source thought to be associated with a black hole. It was time for the moment of truth, the moment of "first light." For Leon Van Speybroeck that first X-ray image, which showed that the mirrors and the imager were going to work, was "almost like a religious experience." For Rick Harnden, the first light through the Imaging Proportional Counter was a moment of anxiety bordering on panic and despair. The Imaging Proportional Counter was viewing a portion of the sky thought to contain the solitary source Cygnus X-3, yet a multiple image appeared. "My first thought was, 'Oh, no! It doesn't work!'" As it turned out, the detector was working just fine. It had discovered a group of previously undetected sources in the vicinity of Cygnus X-3. The other instruments worked well, too. With a successful mission almost guaranteed, the observatory was nicknamed the Einstein Observatory, in honor of the centennial of the birth of the man whose theories of space, time, and matter so radically altered our perception of the universe. After more than a decade and a half of planning, politics, and persistence through the solution of what Tananbaum remembered as "a hundred thousand technical problems of one kind or another," Riccardo Giacconi's dream of a large orbiting X-ray telescope had come true.

While the Einstein Observatory was sending back stunning X-ray images of exploding stars and galaxies and clusters of galaxies, preparations were being made to launch HEAO 3, an observatory that would probe the universe at even higher photon energies and would capture samples of high energy particles from interstellar space. HEAO 3 was similar to HEAO 1 in that it was a survey mission involving several independent but complementary instruments. The restructuring of the HEAO program had forced a marriage of three experiments into one experiment designed to observe rare high atomic number cosmic rays. The Principal Investigators on the new experiment were Martin Israel, Edward Stone, and C.J. Waddington. It was a

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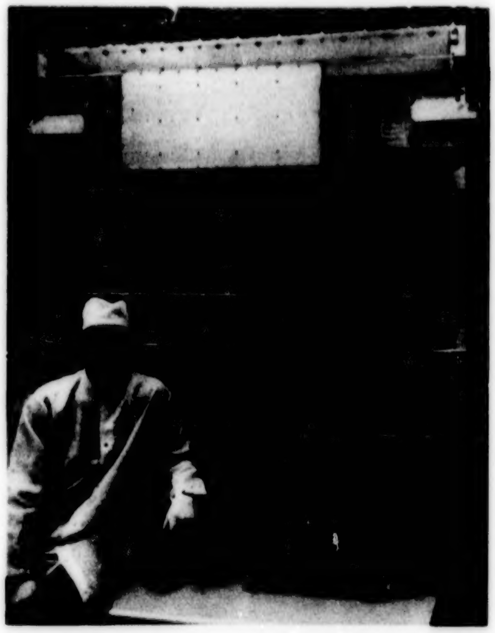
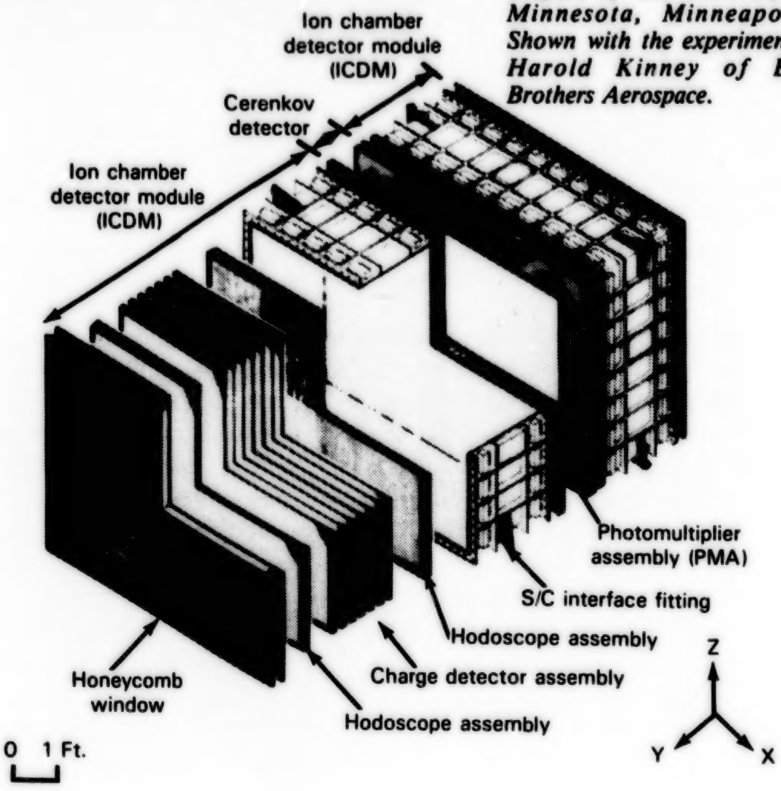


The Heavy Nuclei Experiment, HEAO C-3. This cosmic ray experiment consisted of two large ionization chambers mounted back to back with a large Cerenkov counter between. It observed rare, high atomic number (z less than 30), relativistic nuclei in the cosmic rays. The instrument measured the elemental composition and energy spectra of these nuclei with sufficient resolution to determine the abundance of individual elements from chlorine (z = 17) through at least uranium (z = 92). The Principal Investigators were Martin Israel of Washington University, St. Louis, Missouri, Edward Stone of the California Institute of Technology, and C. J. Waddington of the University of Minnesota, Minneapolis. Shown with the experiment is Harold Kinney of Ball Brothers Aerospace.


Ion chamber detector module (ICDM)
Cerenkov detector
Ion chamber detector module (ICDM)
Photomultiplier assembly (PMA)
S/C interface fitting
Hodoscope assembly
Charge detector assembly
Honeycomb window
Hodoscope assembly
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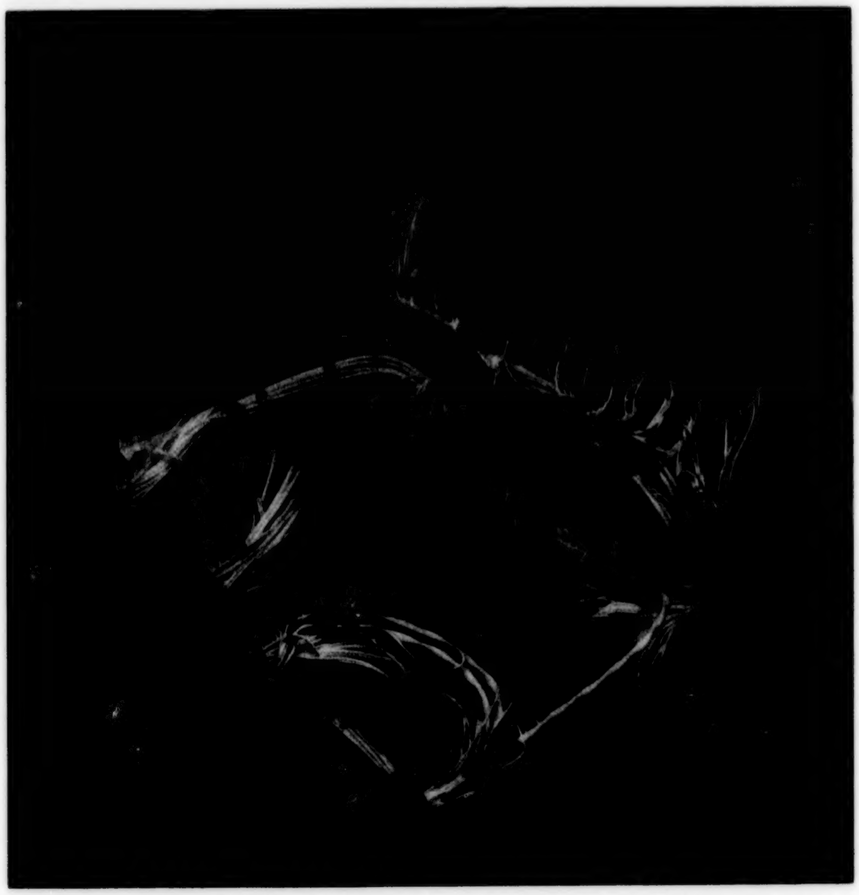

All the data collected by HEAO 3 passed through the main junction box shown here.

marriage of convenience, brought about primarily by budgetary considerations, but by all accounts it was a highly successful union. "The collaboration resulted in a better experiment," said Martin Israel, "because it brought together three different approaches to studying cosmic rays." This made it possible for the experimenters to unambiguously determine both the nuclear charge (atomic number) and momentum of a cosmic ray particle.

The Israel-Waddington-Stone Heavy Nuclei Experiment was one of two cosmic ray experiments on HEAO 3. The other was an experiment designed to measure the isotopic composition of cosmic rays. It was a collaboration between scientists and the Center for Nuclear Studies in Saclay, France, and the Danish Space Research Institute in Copenhagen, Denmark. With the French group there was another collaboration which came about, not because of budget, but because of the keen eye of a young physicist. At the heart of the French-Danish proposal were counters that required a liquid without bubbles and freon gas at very high pressure. Such a counter was proving very difficult to build, and the scientists were worried about being able to develop the required technology in time. As Lydie Koch-Miramond remembers it, "there was this young physicist, Michel Casse, who was interested in becoming part of the project. He was reading through the journals and preprints in the library when he came across a doctoral thesis in applied chemistry. The thesis dealt with a method of growing transparent silica gels. He thought that it could work for our counters. We went to Lyon, talked to the chemist, and began a collaboration that led to a successful counter. If he had not read that thesis, we probably wouldn't have made the second selection [the selection after restructuring] for HEAO."

If HEAO 3 was blessed with serendipitous partnerships, it was also plagued by eleventh hour problems. Within a week of delivery, 100 amplifiers were destroyed in final thermal vacuum testing of the Heavy Cosmic Ray Nuclei experiment. The problem was quickly traced to a faulty testing procedure, so there was no concern about the amplifiers failing in orbit. Nor would it be particularly difficult to replace the destroyed amplifiers. But what about the thousand or so amplifiers that were not destroyed? Were they damaged to the point that they might fail? The only solution was to take them out, test them, and put them back in again. This involved breaking and remaking over one hundred thousand connections or welds.

Then, just four months before launch, the Gamma Ray Spectrometer developed "thermal excursions." In other words, the instrument, designed to operate at 80 K (−315° F), was from time to time heating up to 120 K (−243° F). Under the direction of Allan Jacobson, the Principal Investigator, a "tiger team" of problem solvers was convened, with Frank Schutz as manager and Jim Stephens handling the technical leadership. Their conclusion: the instrument would have to be taken apart. Working sixteen hours a day all through the summer, scientists, engineers, and technicians from the Jet Propulsion Laboratory, TRW, and Ball Brothers Aerospace in Boulder, Colorado, disassembled the instrument and found the problem. A washer had not been squeezed flat by its companion bolt. The result had been a less that perfect seal that caused the thermal excursions.

The seal was repaired, and the Gamma Ray Spectrometer was rushed by Military Air Transport to the Kennedy Space Center launch site, where it was installed in the spacecraft just hours before the Center was evacuated in preparation for Hurricane David. Two weeks later, on September 20, 1979, HEAO 3, the last of the HEAOs, was successfully launched. A few days later the instruments were turned on, and it was clear that the mission would be a success.

Some of the many scientific successes of the HEAO program will be discussed in the chapters that follow. The point to be made here is that it was also a tremendous technological success. As Frank McDonald said, "HEAO showed that you could put together very large experiments that in

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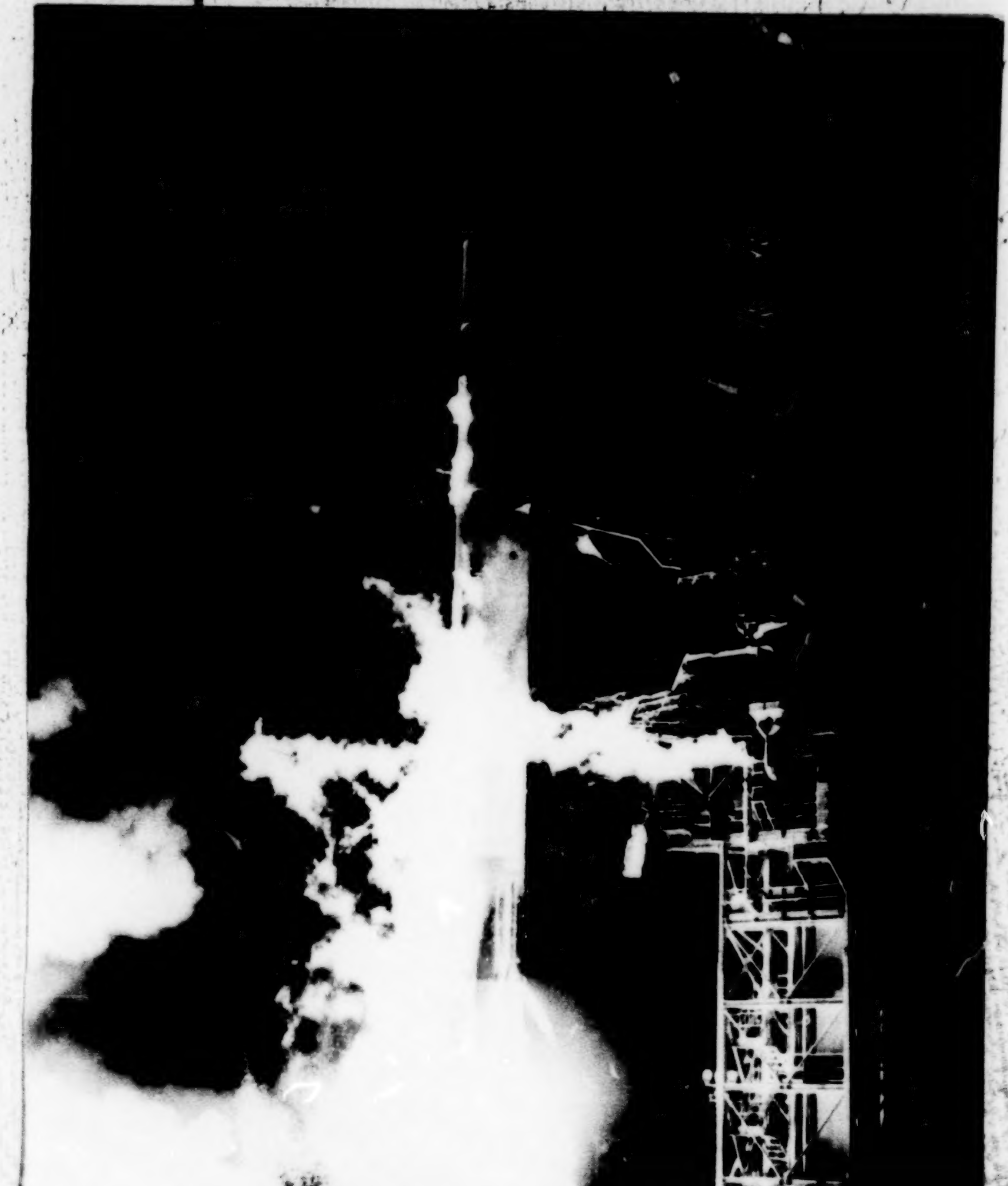
many cases exceeded expectations of design." And it was done within 20 percent of the original cost estimate, an amazing feat considering the complexity of the project and the fact that the consumer price index for commodities and services increased by more than 50 percent over the same period.

HEAO worked in part because it was well planned and well managed. But most of all it worked because of the talent and the extraordinary dedication of the individuals involved. And the dedication of their families, who must have wondered sometimes if all the long hours, the lost weekends and vacations, and the distracted, worried looks across the dinner table were really worth it. "We had to get a lot out of people through perseverance, argument, and friendships forged during the years of the project," recalled Steve Murray. "A lot of times the engineers went the extra mile with us simply because they were our friends." Friendships were part of it, to be sure, but they were not the driving force that kept these people working overtime without pay day after day for years. Friendships could not explain why Harold Kinney, a mechanical technician on HEAO 3, could say, "there

Ball Brothers Aerospace workers reinsert the repaired cryostat into the Gamma Ray Spectrometer refrigerator.



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was not one morning during the whole project that I didn't want to come to work." What could explain it?

Dozens of scientists and engineers involved with the HEAO program were asked this question. Their responses were almost all the same and related to two deep-seated human desires: the desire to solve problems and the desire to be a part of something larger than themselves. "The most gratifying thing was to solve the problems," said Harvey Tananbaum. "There was no finger pointing as to why the problems had arisen, just recognition that a tremendous problem had been solved. Everyone was working together." Dick Halpern summed up the feeling: "I was once asked who was most responsible for HEAO's success and I couldn't answer. Hundreds of people worked on the project. Sure, I knew many, many of them — but all of them felt responsible — and they all were." And finally, as Art Gneiser of Ball Brothers put it, "It's an incredible feeling of satisfaction to see the data come in, bringing information about the universe out there, and to know that a lot of yourself is up there and that it's all working."

7

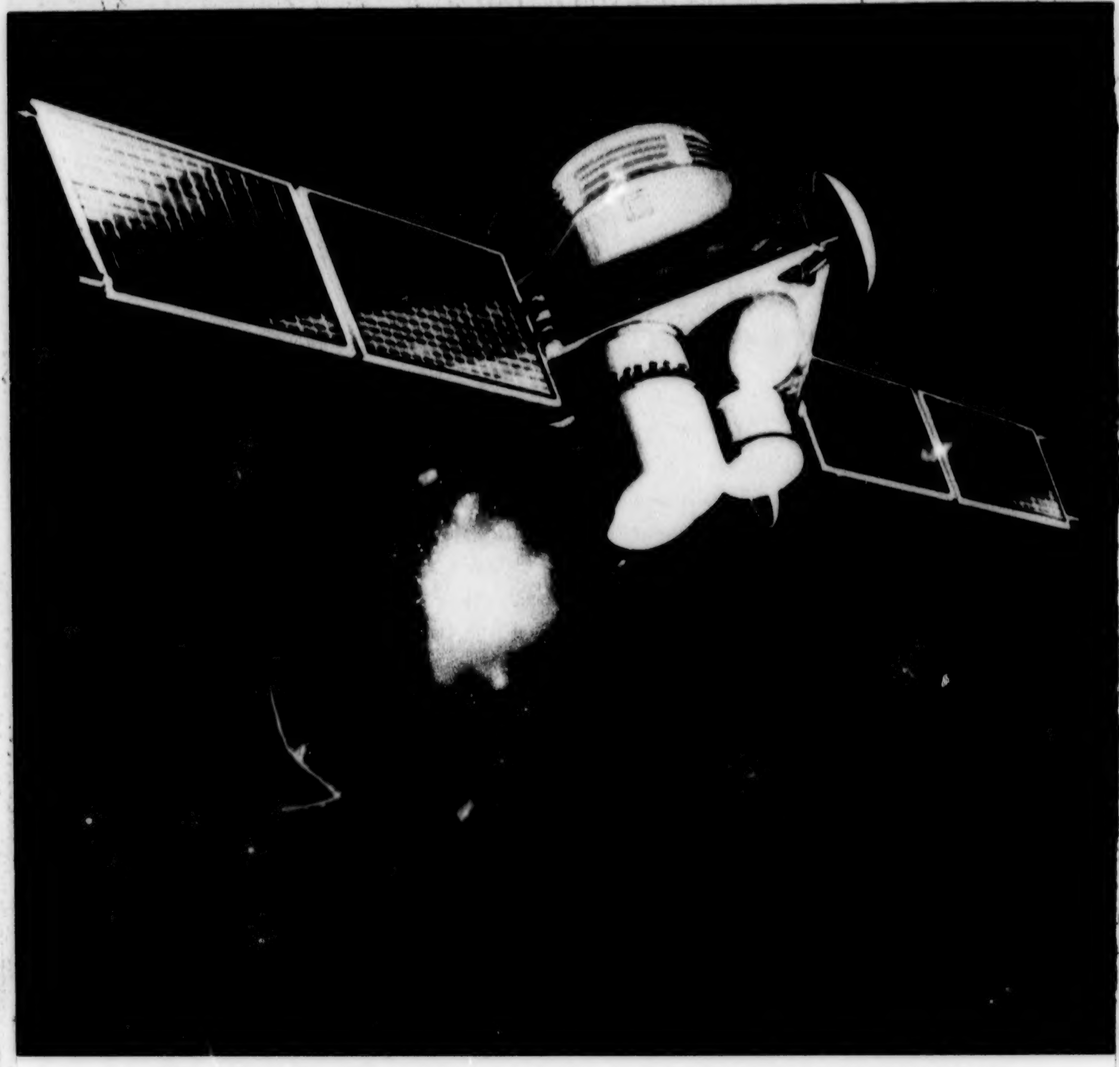
NEW PERSPECTIVES IN ASTRONOMY

The data from the HEAOs have opened wide a new window on the universe, allowing us to see the universe from a new perspective, the high energy perspective. As discussed in the chapters to come, because of these three observatories we have increased our understanding of such diverse phenomena as flare stars, newly formed stars, exploding stars, collapsed stars, black holes, the center of our galaxy, other galaxies, clusters of galaxies, and quasars. We have been able to apply this knowledge to questions ranging from the origin of the elements to the size of the universe.

The HEAOs, especially the Einstein Observatory, have changed astronomy in another way. As Herb Gursky pointed out, "Astronomers traditionally have looked to ground-based optical information as the key to astronomical understanding. With Einstein that has changed." The reasons for this change are (1) virtually every known astronomical object, from stars to quasars, has been found to emit measurable X-rays; (2) the quality of data, in terms of spatial and spectral resolution, is comparable to that obtained in the optical region; (3) many phenomena are seen that are invisible with optical telescopes; and (4) large numbers of astronomers have access to the Einstein data as part of a guest observer program.

From the beginning, one of the goals of Riccardo Giacconi and the other members of the Einstein Observatory consortium was to bring X-ray astronomy into the mainstream of astronomy. To do this they not only had to build an observatory that would collect data with a quality of that comparable to the large optical telescopes, they also needed a broad segment of the astronomical community to have access to and contact with the data. To this end, the HEAO scientists and NASA agreed to institute a guest observer program. According to this program, which was administered by Fred Seward of Smithsonian, 20 percent of the observing time for the first year was reserved for guest observers, with an increased percentage reserved for guests after the first year. Over 400 guest observers from over 50 different institutions were accommodated in this way. Thus, in Gursky's words, "Einstein became a universal facility both from the point of view of the range of astronomical phenomena that it can investigate and the vast number of individuals that have access to it. Thus not only the fact but the perception has changed," namely, that astronomy is best done by looking at the universe over a wide range of wavelengths.

The launch dates, the dates on which they ceased operation, and the dates of reentry into the atmosphere are listed in the following table for the



The Gamma Ray Observatory, now under construction and scheduled for launch near the end of the 1980s, will carry gamma ray telescopes that will surpass those of previous gamma ray detectors by an order of magnitude or better.

three HEAO spacecraft. Although the spacecraft no longer exist, the analysis of the data from the HEAO missions will continue for years, and important new results will be discovered as astrophysicists mine the rich lore of the HEAO data banks. Rather than attempt a complete survey of the scientific results from the HEAOs, I will give a sampling of the results that should impart the flavor and scope of the new discoveries and their impact on our understanding of the universe. Hundreds of scientists from many different institutions have contributed to the work described below; because of their large number, I have regrettably found it impractical to mention them individually by name or to cite their papers. For these important details I refer the reader to the books and journals listed under Additional Reading at the end of the book.

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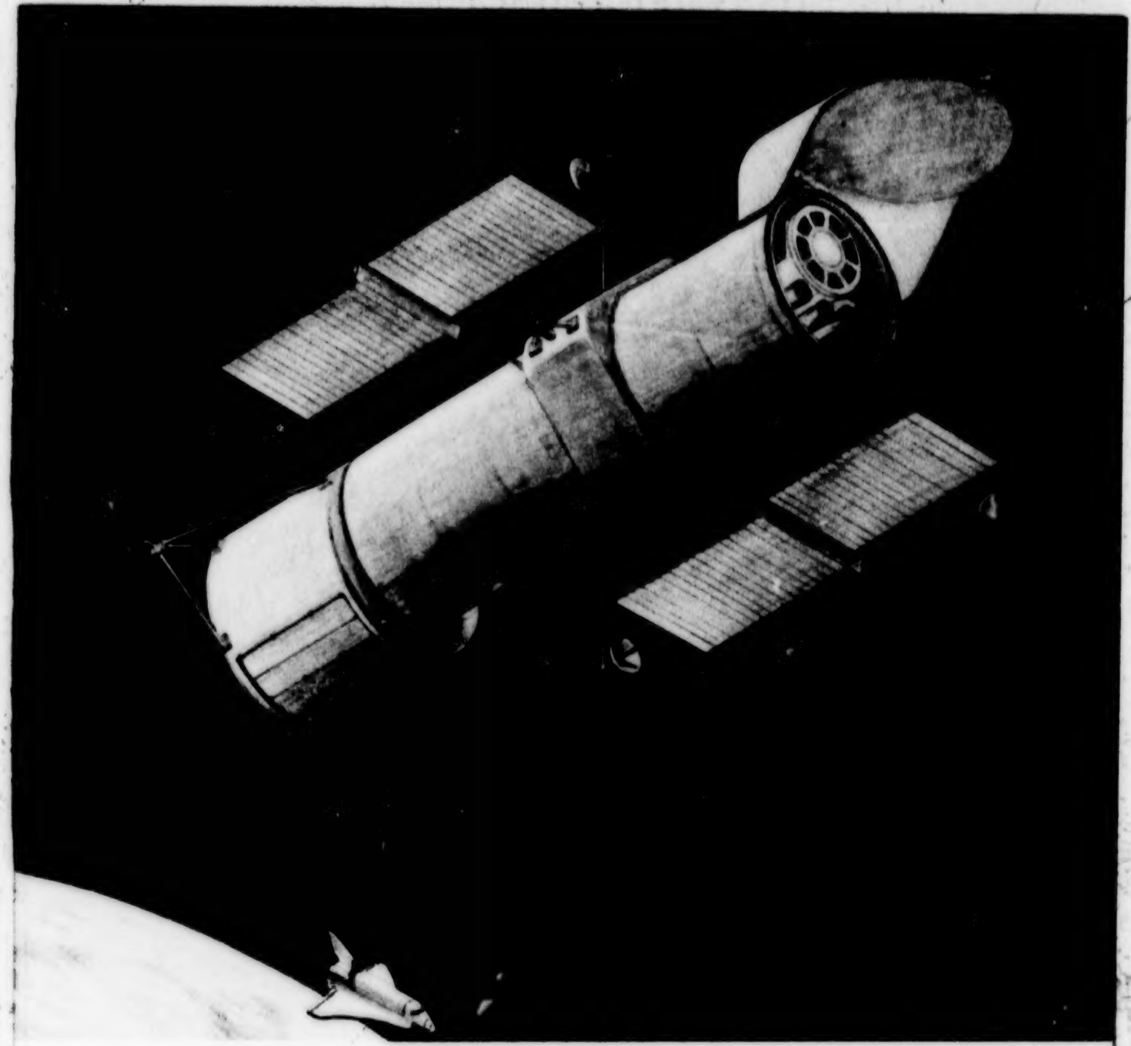

The Advanced X-Ray Astrophysics Facility has been designated as the highest priority new project in U.S. astronomy for the 1980s by the Astronomy Survey of the National Academy of Sciences. The facility would be launched by the Space Shuttle and be resupplied in orbit. It should have a lifetime of 10 to 15 years. With a 1.2 meter diameter mirror and improvements in the focal plane instrumentation, it should be a hundred times more sensitive than the Einstein Observatory. (Courtesy Harvey Tananbaum)

Launch, Termination, and Reentry Dates for HEAO Missions

Mission	Launch	Ceased operation	Reentry
HEAO A	12 Aug 1977	9 Jan 1979	14 May 1979
HEAO B	13 Nov 1978	26 Apr 1981	25 Mar 1982
HEAO C	20 Sep 1979	30 May 1981	7 Dec 1981

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Part Three

THE HIGH ENERGY UNIVERSE:

A Survey of the Results from the High Energy Astronomical Observatories

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CREATIVE VIOLENCE

A high energy universe is almost by definition a violent one. That is too bad, you might say. Life would be far more pleasant in a nonviolent universe. Not necessarily. Violence has its uses, even for a species as fragile as our own. It is not simply a "force used so as to injure, damage or destroy," to give the dictionary meaning. It can be, indeed it is, a creative force in nature that has made life as we know it possible.

Without the violence of volcanos, life might never have spread across the face of Earth. Water, that essential ingredient for the development and sustenance of higher forms of life, might have remained forever locked deep in the interior of Earth if it had not been brought to the surface by volcanic eruptions and violent geysers.

Looking at things from a somewhat larger perspective, it is probable that the Sun and all the planets of the solar system would not be here but for violence on a much grander scale. The vast amorphous cloud of dust and gas from which our solar system was formed might still be a formless mass if an interstellar shock wave had not triggered the collapse of the cloud.

About once every 50 years, one of the massive stars in our galaxy blows itself apart in a supernova explosion. The force of the explosion hurls vast quantities of radiation and matter into space and generates shock waves that sweep through the arms of the galaxy. The shock waves heat the interstellar gas, evaporate small clouds, and compress larger ones to the point at which they collapse under their own gravity to form new stars. The recent discovery of meteorites with anomalous concentrations of certain isotopes indicates that a supernova might have precipitated the birth of our solar system more than four and a half billion years ago.

The cloud that collapsed to form the Sun and the planets contained an important legacy of stars that exploded even longer ago. Although composed mostly of hydrogen and helium, the cloud was enriched with carbon, nitrogen, and oxygen, elements that are essential for life as we know it. All the elements heavier than helium are manufactured deep in the interior of stars and would for the most part remain there if it were not for the cataclysmic supernova explosions that blow giant stars apart.

Supernovas are the creative flashes that renew the galaxy. They seed the interstellar gas with heavy elements, heat it with the energy of their radiations, stir it up with the force of their blast waves, and cause new stars to form. Some of these stars will be massive. They will rush through their life cycle, explode, dump a new supply of heavy elements into the gas, and

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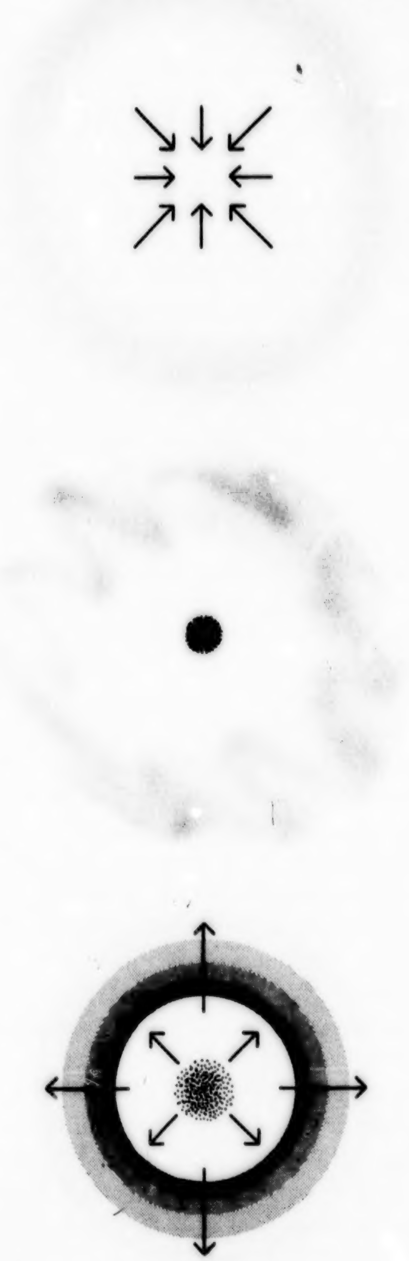

When the nuclear fuel in the core of a large star has been exhausted, the matter in the core will be compressed to form a collapsed star. This will generate an outward impulse that produces a supernova explosion that blows apart the rest of the star.

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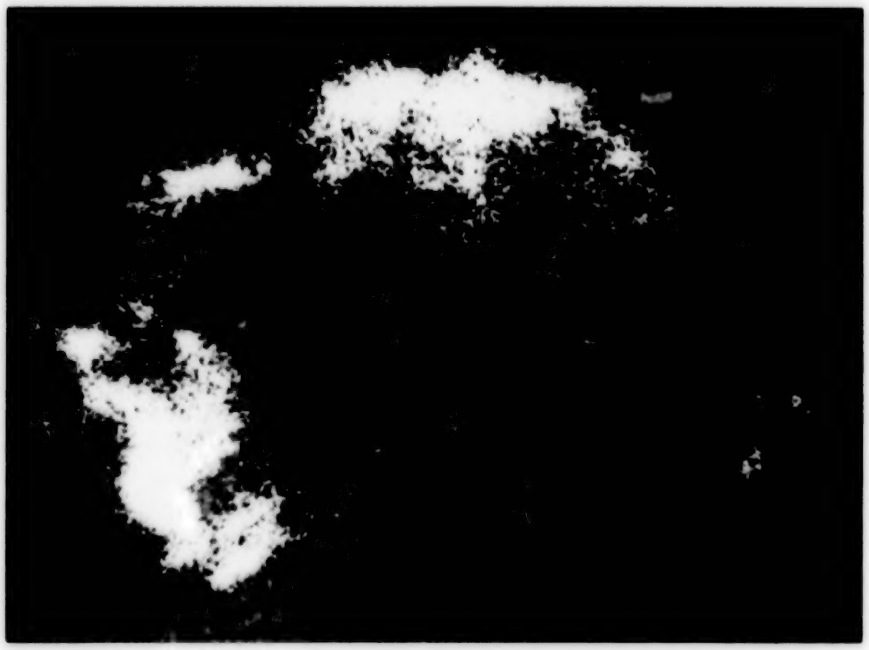

Einstein Observatory X-ray image of the supernova remnant Cassiopeia A. (Courtesy of Steve Murray)

quite possibly trigger the formation of other stars to make other supernovas in a chain of violence that links the rise of life on Earth to events billions of years and half a galaxy away.

Once life was established on Earth, it might have been affected by supernova explosions in a more subtle but nonetheless crucial way. Supernovas produce clouds of high energy particles, the cosmic rays. Cosmic rays generated in supernovas and other processes form a background of high energy particles that continually rain down on Earth, producing many of the genetic mutations thought to be responsible for driving the evolution of the species.

The general picture that has been developed for the supernova explosion and its aftermath goes something like this. Throughout its evolution, a star is much like a leaky balloon. It keeps its equilibrium figure through a balance of internal pressure against the tendency to collapse under its own weight. The pressure is generated by nuclear reactions in the core of the star which must continually supply energy to balance the energy that leaks out in the form of radiation. Eventually the nuclear fuel becomes exhausted, and the pressure drops in the core. With nothing to hold it up, the matter in the center of the star collapses inward to higher and higher densities and temperatures until the nuclei and electrons are fused together into a superdense lump of matter known as a neutron star. As the overlying layers rain down on the surface of the neutron star, the temperature rises until, with a blinding flash of radiation, the collapse is reversed. A thermonuclear shockwave runs through the now expanding stellar envelope, fusing lighter elements into heavier ones and producing a brilliant visual outburst that can be as intense as the light of 10 billion suns.

The shell of matter thrown off by the explosion plows through the surrounding gas, producing an expanding bubble of hot gas, with gas temperatures in the millions of degrees. This gas will emit most of its energy at X-ray wavelengths, so it is not surprising that X-ray observatories have provided some of the most useful insights into the nature of the supernova phenomenon.

More than 20 supernova remnants have now been detected in X-rays. Studies of these sources have provided the best estimates of the energy released in a supernova explosion. The powerful instruments aboard the HEAOs have gathered information that should clarify our understanding of the interaction of the expanding shell with the surrounding interstellar gas and the mechanism for producing cosmic rays. They should also help us to unravel such fundamental questions as how much of the ejected mass is in the form of heavy elements, and whether or not a neutron star is always left behind at the center of the remnant.

In the next few chapters the HEAO results on supernova research are discussed together with how they affect our understanding of such diverse problems as the creation of heavy elements, the origin of cosmic rays, the nature of pulsars, the formation of stars, and the large-scale structure of the galaxy.

9

EXPLOSION OF A STAR AND A MYTH

An exploding star. To the sixteenth century mind this was as absurd as a flying elephant. It just did not happen. It was contrary to the order of nature according to which stars belong to the ". . . ethereal region of the celestial world which is free from change or corruption." The stars were symbols of the eternal and unchangeable, part of a system of permanence standing above the ever-changing, ever-corruptible world below.

Then, in November 1572, a star brighter than the planet Venus appeared suddenly in the constellation of Cassiopeia. It was noticed throughout Europe and in the Far East. The New Star or Nova of 1572 would shatter forever man's belief in the incorruptibility of the stars. The man most responsible for this rearrangement of the cosmic landscape was Tycho Brahe, a stormy, roisterous astronomer known for his acid tongue and silver nose.

Tycho, who wore a prosthetic silver nose to replace the one he had lost in a duel at age twenty, made accurate measurements of the position of the star relative to the other stars in Cassiopeia. For 18 months, though the brightness of the star declined steadily until it became invisible, its position remained fixed. This proved that the new star, or Stella Nova, belonged to the "eighth sphere" of the fixed stars.

Today, more than 400 years later, we use the word supernova to describe Tycho's object, even though we now know that it was not a new star at all. It had been there for tens of millions of years or more, invisible to the naked eye because of its distance of more than 6000 light years. It became visible at the end rather than the beginning of its evolution, as it underwent a catastrophic explosion.

The remnant of Tycho's supernova was singled out for study by the HEAOs because it is relatively young and is still glowing brightly in X-rays. We know when the supernova explosion occurred, and, thanks to Tycho, we know a good deal of its early history. It presents one of the best opportunities to study the interaction of the exploded star with the interstellar gas around it and to determine the mass and composition of the ejected material. Only through such comparisons can we check the theories that purport to explain the mechanisms of supernova explosions, the origin of the elements, and the origin of cosmic rays.

Most of the energy emitted by Tycho's supernova remnant falls in the X-ray band. There it gives off several billion times more X-rays than does the Sun and more energy than several hundred suns would emit at all

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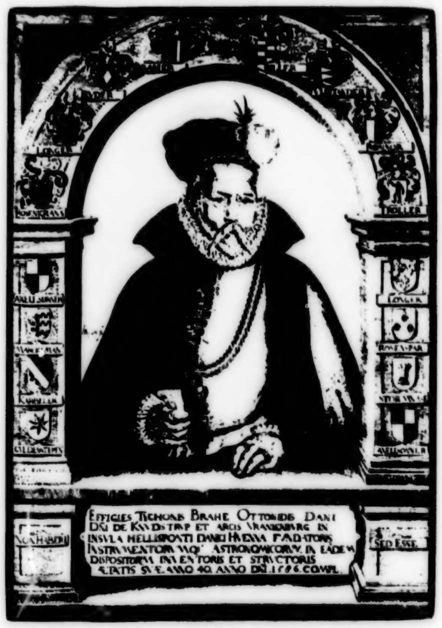
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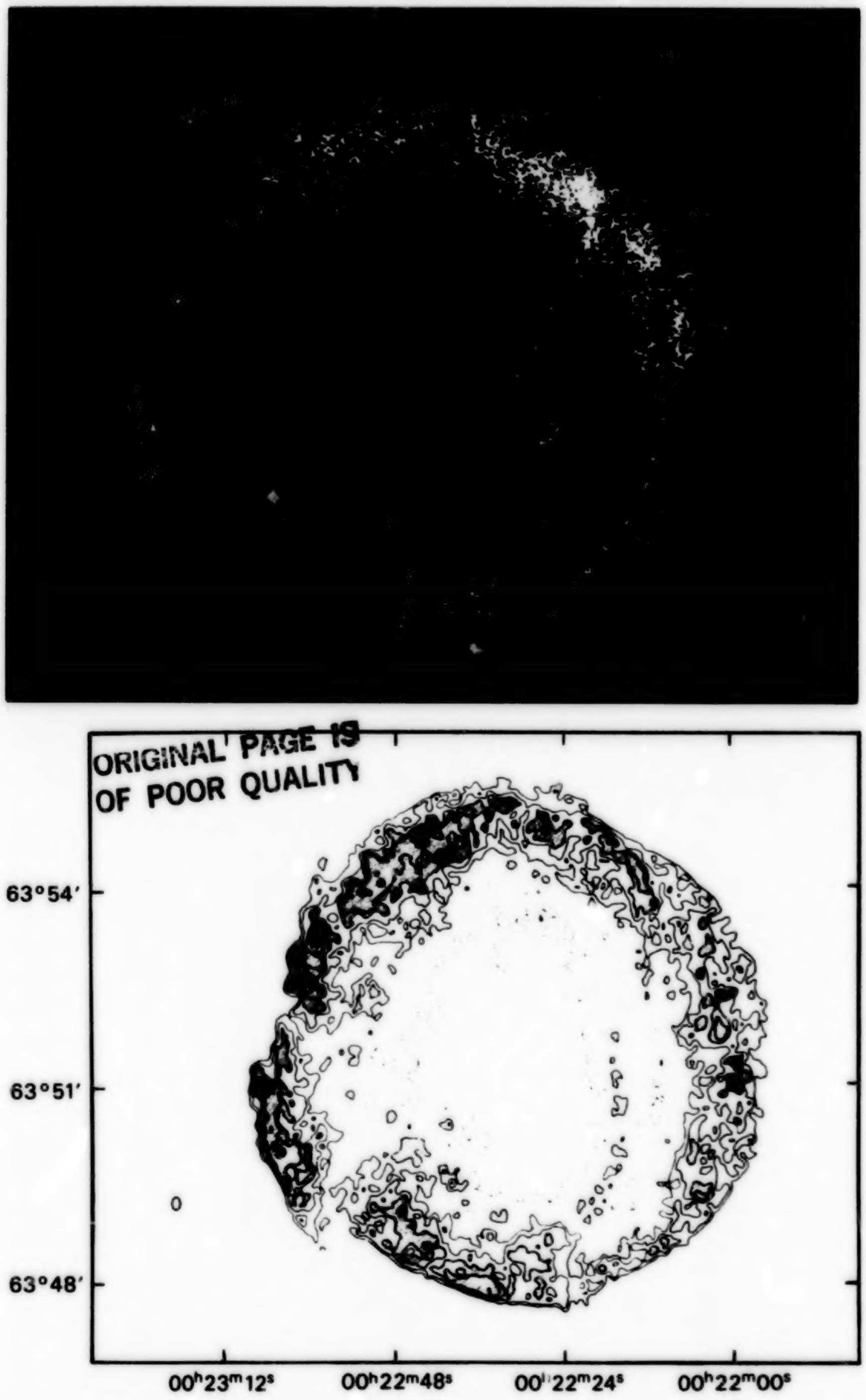
Tycho Brahe

wavelengths. Relatively little energy comes from the supernova remnant in the form of optical radiation, and even less in radio waves.

That is not to say that the radio waves are unimportant. On the contrary, the sensitivity of giant radio telescopes is such that the remnant of Tycho's supernova was first discovered in 1952, using the Jodrell Bank radio telescope. Shortly thereafter, faint optical wisps in the same location were discovered using the 200-inch telescope at Mt. Palomar.

The radio discovery of Tycho's supernova remnant was a watershed in astronomy. It demonstrated the usefulness of radio telescopes in searching for the remnants of supernova explosions. The technique developed rapidly, until today no nebula is considered to be a certified supernova remnant unless it possesses the characteristic signature of radio emission of high energy electrons.

Observations show that the radio waves in supernova remnants are produced by the synchrotron process, named after a phenomenon first observed in synchrotron particle accelerators, namely, the emission of strongly polarized radiation by very energetic electrons spiraling along a magnetic field. The shells of supernova remnants are filled with magnetic energy and enormous numbers of charged particles bouncing around the shell at speeds very near the speed of light. This situation is not unique to Tycho's supernova remnant. Every supernova remnant somehow produces large quantities of extremely high energy particles. Clearly, supernova remnants are efficient particle accelerators and play an important role in producing the high energy particles, or cosmic rays, that constantly bombard Earth. How do they do it?



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The striking similarity of the X-ray (top) and radio (bottom) images of the Tycho supernova remnant provides strong evidence that the same phenomenon, namely, the shock wave produced by the supernova, is responsible for both types of radiation. [Einstein Observatory X-ray image courtesy Paul Gorenstein; radio map from R. Strom et al. Monthly Notices Royal Astron. Soc. 200, 473 (1982).]

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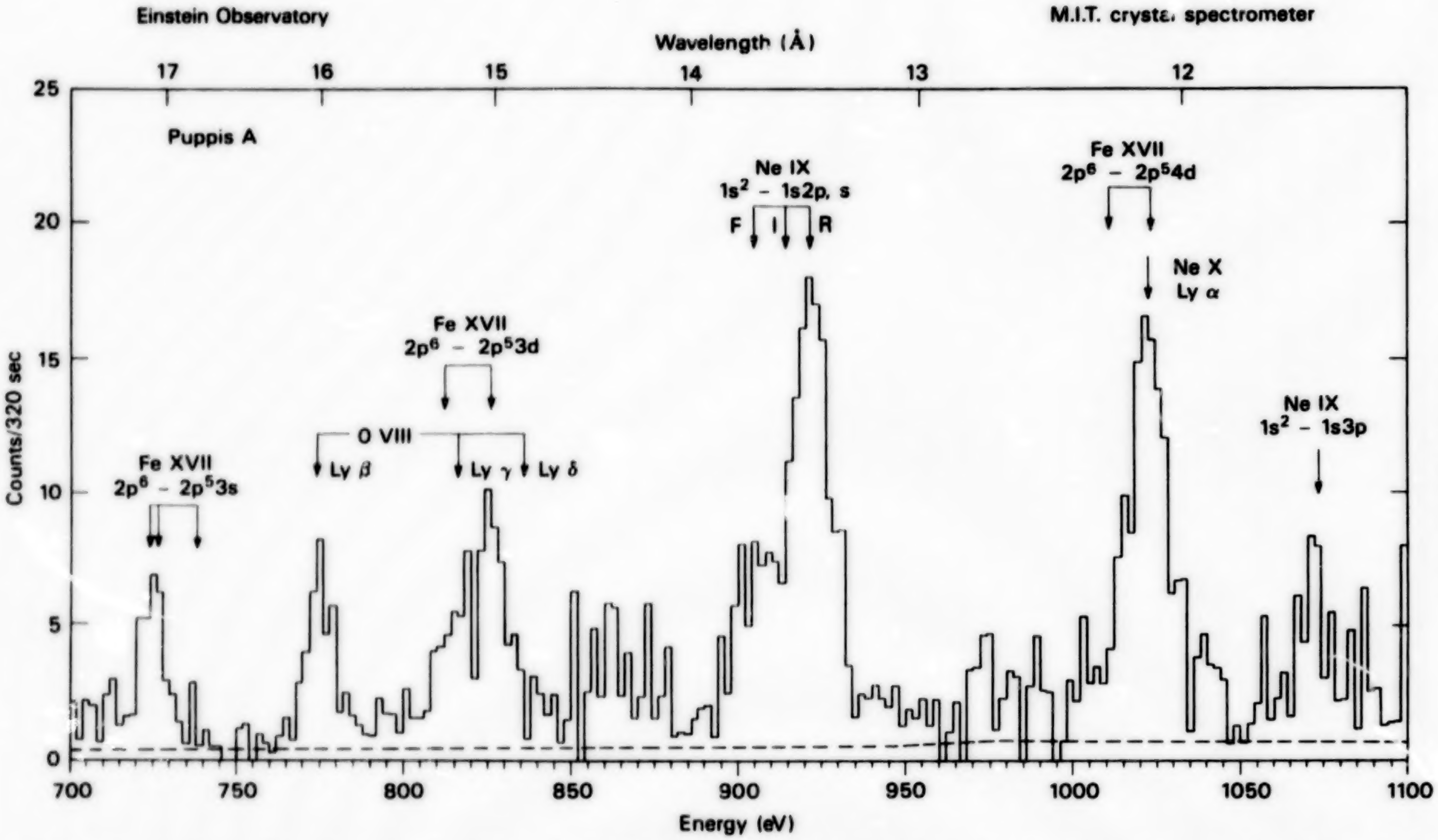
An X-ray image of the Puppis A supernova remnant. (Einstein Observatory image courtesy G. Clark and C. Canizares)

The initial explosion cannot explain the high energy particles observed in supernova remnants. Particles produced then will quickly lose their energy as they cool in the expanding cloud, or they would have escaped from the remnant. In two supernova remnants, the Crab Nebula and the Vela supernova remnant, a rapidly rotating neutron star, or pulsar, is generating large quantities of high energy particles. These objects appear to be the exception rather than the rule, however. In most cases the acceleration of particles to high energies must have something to do with the shock wave produced by the supernova explosion. It is here that X-ray astronomy has made an important contribution.

If the high energy electrons producing the radio emission are generated in a supernova shock wave, and the shock wave is known to produce a very high temperature X-ray emitting gas, then the X-ray and radio images of a supernova remnant should be very similar. The accompanying figures show that the X-ray and radio maps are strikingly similar. The X-ray and radio maps of two other supernova remnants known as Cassiopeia A, Puppis A, and SN 1006 also show a close correspondence between radio and X-ray images.

A close inspection of high resolution X-ray images of the supernova remnants shows that the X-ray emitting shell has broken up into many small fragments. It has been suggested that these fragments represent turbulent



The X-ray spectrum of supernova remnant Puppis A shows strong emission lines from the elements oxygen, neon, and iron. The strength of these lines is consistent with the idea that the supernova ejected material rich in these elements into the interstellar medium. [P. F. Winkler et al. Astrophys. J. 246, (1981).]

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magnetic eddies and that charged particles are accelerated to very high energies through collisions with the fragments. The acceleration process is analogous to that of a ping pong ball moving through a collection of randomly moving bowling balls. Over the course of many collisions, the ping pong ball will be accelerated to a very high speed. It is too early to say definitely that the size and number of fragments are adequate to generate the high energy electrons and magnetic field necessary to explain the radio emission and, ultimately, the cosmic rays that reach Earth, but a preliminary analysis looks promising.

By examining the radiation from young supernova remnants in detail, we can test other ideas about the role of supernova explosions in the scheme of things. For example, are the medium-heavy elements, such as oxygen, neon, silicon, sulfur, calcium and iron, produced there? If so, then we might expect to find an enrichment of these elements in the shells thrown off by supernova. Observations with the spectrometers of the Einstein Observatory have borne out this expectation. The gas producing the X-rays shows an excess of emission associated with the medium-heavy elements. The excess emission could be due to some peculiar nonequilibrium conditions in the shock wave. More likely, however, we are seeing a concentration of elements made inside a star and blown into the interstellar gas, where they will ultimately be mixed with that gas.

On Earth, these elements are so common – most of the dirt and sand is silicon – that we take them for granted. Yet they are not common at all in the universe at large and would never have been here, indeed we would never have been here, if it were not for a long chain of events that can be traced back to a star that exploded somewhere in the galaxy more than four and a half billion years ago. Today, we are gaining confidence that we understand some of the first and most fascinating links in this chain, thanks to the power of the HEAOs, and thanks also to the astronomer with the silver nose.

10

COSMIC RAY SURPRISE

The HEAO X-ray experiment has shown that remnants of exploded stars, supernova remnants, are enriched in the medium-heavy elements such as oxygen, silicon, and sulfur. These observations provide strong confirming evidence for the evolution of stars, according to which medium-heavy elements are synthesized in massive stars and thrown into space by the explosion of these stars.

Another, more elusive prediction of stellar models is that many of the heavy elements, for example, arsenic, strontium, radium, and uranium, are built up very rapidly from lighter elements during the actual explosion. Add to this the long-standing belief that cosmic rays are also produced as a result of a supernova explosion, and you have a testable prediction, namely, that cosmic rays should show an enrichment of the rapidly processed, or r-process, heavy elements.

Several cosmic ray experiments before the HEAO program seemed to support this prediction; thus, when the results from the HEAO cosmic ray experiments came in, many astronomers were in for a surprise. The Heavy Nuclei Experiment and the Cosmic Ray Isotope Experiment showed convincingly that there is no significant enrichment of r-process elements in the cosmic rays. The relative amounts, or abundances, of each element are quite similar to the relative abundances of the elements in the solar system. In addition, the HEAO C Gamma Ray Spectroscopy Experiment set limits on the abundance of certain nuclei that should have been produced in supernova explosions over the lifetime of the galaxy. These limits are significantly below theoretical predictions.

What are the implications of these findings? They mean that either the r-process buildup of heavy elements does not occur in supernova explosions, or that cosmic rays do not originate in the remnants of supernovas. Recent theoretical and observational work suggests that both these statements are true.

Recent theoretical work has shown that the r-process is probably not very efficient in supernova explosions after all, that the most likely place for it to occur is in the core of a star about the size of the Sun. Such stars are very common and will never become supernovas because their masses are not large enough. However, when the core of a solar-type star exhausts its hydrogen fuel, it collapses until it ignites thermonuclear reactions based on the fusion of helium nuclei. This ignition, which is called the helium flash, has the character of a thermonuclear explosion and apparently occurs

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several times until the core of the star settles down. The helium flashes are not sufficiently violent to blow the star apart, but they can apparently produce large enough fluxes of neutrons to make the r-process work. Thus, the standard dogma that all the heavy elements are produced in supernova explosions may have to be revised.

What about the idea that cosmic rays are produced as a result of supernova explosions? As we shall see, the standard view may be in trouble.

First of all, remember that cosmic rays are high energy particles. Their speed is very close to the speed of light, the ultimate speed that any particle can attain. How cosmic rays reached such high speeds is the central problem in understanding the origin of cosmic rays. There are many proposed solutions to this problem, but no accepted ones. All the proposals have a common thread, namely, that the force that accelerates the cosmic rays to high energies is the electrical force.

Charged particles moving through a high electrical voltage drop can achieve high energies if the voltage drop is large enough. The voltage drops required to explain the cosmic rays observed by the HEAO 3 experiment range upwards from millions of volts to many billions of volts.

The cosmic rays must have moved through a very powerful electrical field at one time, or else traversed smaller electrical fields many times. The first situation could be realized in the vicinity of the rapidly rotating, highly magnetized collapsed stellar cores, known as pulsars or neutron stars, that are sometimes left behind as remnants of supernova explosions. Alternatively, a charged particle could be trapped in the violent shock wave produced by a supernova explosion. As it bounces back and forth in the shock wave, the charged particle would traverse an electrical field many times and be accelerated up to very high energies. Radio, optical, and X-ray observations of the compact pulsars and extended supernova shells have shown that electrons can in fact be accelerated to very high energies in both situations. The protons and other heavy particles that make up most of the cosmic rays do not radiate as efficiently as electrons, so they cannot be observed directly. Nevertheless, it was assumed, with good reason, that supernova explosions were responsible for the cosmic rays.

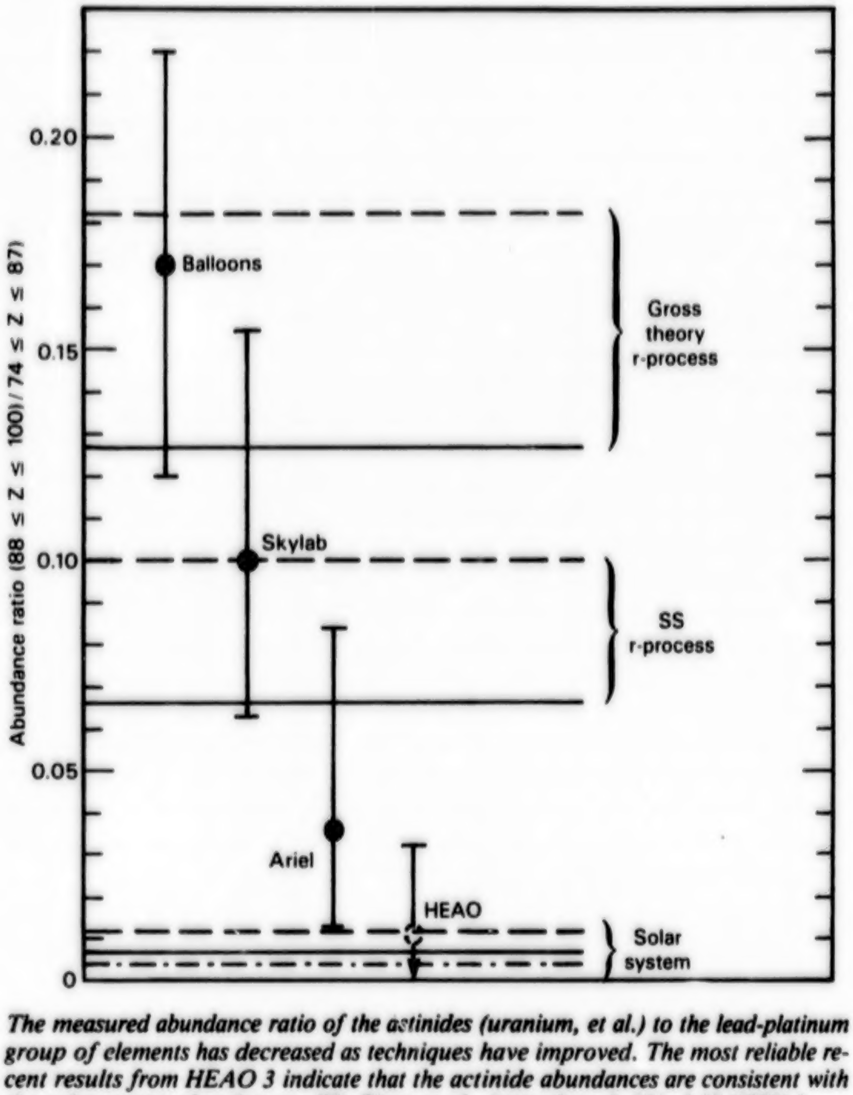
Here again, experiment had another surprise in store for the theoreticians.

The relative abundances of the elements in the cosmic rays observed by the HEAO 3 experiment are similar to the relative abundances of the elements in solar system material, but they are not identical. The differences may contain important clues as to how cosmic rays originate.

It is observed that the elements that are more difficult to ionize are less abundant in the cosmic rays than in solar system material. For example, it takes about twice as much energy to tear an electron away from, or ionize, an oxygen atom as it does to ionize an iron atom, and the amount of oxygen relative to iron in cosmic rays is about half the relative amount found in the solar system.

This general trend, which had been suggested on the basis of earlier experiments, was confirmed by HEAO 3 for a wide range of elements, from oxygen through zirconium. This behavior is difficult to understand if cosmic rays are produced by violent events such as supernova explosions. The atoms should be completely stripped of all their electrons under such conditions; the amount of energy required to tear off the outermost electron should be irrelevant.

On the other hand, if cosmic rays originate in a comparatively low energy environment having a temperature of about 10 000 degrees, the



The measured abundance ratio of the actinides (uranium, et al.) to the lead-platinum group of elements has decreased as techniques have improved. The most reliable recent results from HEAO 3 indicate that the actinide abundances are consistent with the solar system abundances. [W. Binns et al. Astrophys. J. 261, L17 (1982).]

ionization energy may have an important selection effect. Under such conditions, some elements would be completely ionized and some would not. For example, relatively more iron atoms than oxygen atoms would have lost an electron. When an atom loses a negatively charged electron, the electrical neutrality of the atom is destroyed. It becomes a positively charged ion. This has important consequences for the acceleration of the particles. If an atom, which is electrically neutral, is placed in an electric field, it is not accelerated by the electric field. On the other hand, an ion, being charged, will feel an electrical force and will be accelerated.

This means that if a gas composed of a mixture of neutral atoms and ions is subjected to an electric field, only the ions will be accelerated. In particular, if the gas has a temperature of about 10 000 degrees, then relatively more iron will be accelerated than oxygen, since relatively more iron atoms will be ionized. This is what is observed in the cosmic rays.

The implication is that cosmic rays do not originate in the high energy environs of exploding stars, but in comparatively more peaceful conditions. These conditions may be found on the edges of hot bubbles carved in interstellar space by hot young stars, around red dwarf stars known for their frequent, intense flares (flare stars), or in the wake of a shock wave which has been plowing through the interstellar medium for hundreds of thousands of years and lost much of its intensity.

Another idea, which may fit in with a supernova origin and the observed relative abundances, traces the origin of cosmic rays to dust grains in the interstellar medium. The observed abundances of these grains are consistent with the relative abundances of cosmic rays. Epstein proposes that the grains themselves are swept up and accelerated by the shock front of a supernova explosion. While interacting with the ambient gas in the shock wave, the grains' electrons are blown off. The ionized grains are accelerated to high speeds and break up through collisions with other grains or with high energy particles into a number of heavy ions. These ions then reenter the shock front and are accelerated to speeds near the speed of light.

These new ways of thinking about the origin of cosmic rays have been stimulated by the excellence of the high energy astronomy experiments. Once again, as it always must, the data, the cold hard facts, have tempered the theories and opened up new pathways for exploration. Bold ideas are needed, to be sure, but only by gathering data to check these ideas can we hope to arrive eventually at some reasonably accurate picture of the universe in which we live.

11

SUPERBUBBLES

It has been known for some time that supernovas profoundly affect the interstellar medium over distances of several light years, sweeping interstellar gas up into shells that glow in radio, optical, and X-radiation for tens of thousands of light years. In the past few years it has become apparent that the effects of a supernova are much more dramatic. They evidently play a major role in the formation of solar systems such as our own, as well as the structure and evolution of the galaxy as a whole.

Some of the latest evidence comes from data collected by the A-2 X-ray experiment aboard the first NASA HEAO. In the course of a search of the HEAO 1 data for X-ray emission from normal stars, a group of scientists came across a previously uncatalogued source. The X-ray map showed that the X-rays did not come from a point-like source, as might be expected from a star. Rather, they were spread out over a large region. The scientists thought they had discovered a new supernova remnant, that is, a cloud of hot gas generated by a supernova explosion.

However, when they looked at X-ray data from adjacent parts of the sky, they found to their surprise that the new source was much larger than a normal supernova remnant. The cloud of gas, which has a temperature of several million degrees, stretches across more than a thousand light years; it contains a gaseous mass equal to that of several hundred thousand suns. Supernovas can produce bubbles of hot gas. A dozen or more of these have been observed. But the bubbles from supernovas have diameters ranging from several light years to slightly more than a hundred light years. The Cygnus superbubble is 10 times larger than the large supernova remnants, occupies 1000 times more volume, and contains 20 times more energy.

The X-rays do not tell the whole story. Radio and optical observations show that the superbubble is surrounded by a shell of cooler hydrogen gas and a network of glowing gaseous filaments. The shell is expanding at a rate of about 10 km per second, or about 20 000 miles per hour as it is pushed outward by the pressure of the hot gas in the superbubble. From the dynamics of the expansion and the observed size of the superbubble, its age can be estimated at about three million years. Near the center of the bubble is a closely bunched group of bright young stars. These stars are surrounded by a smaller bubble of gas that, because of its relatively low temperature (10 000 or 20 000 degrees), shows up best in radio band, where it is one of the strongest sources in the sky. The Cygnus superbubble is not an isolated example. Radio, optical, and X-ray astronomers have discovered a number of objects, called supershells, rings, spurs, etc., that are most probably superbubbles in various stages of evolution.

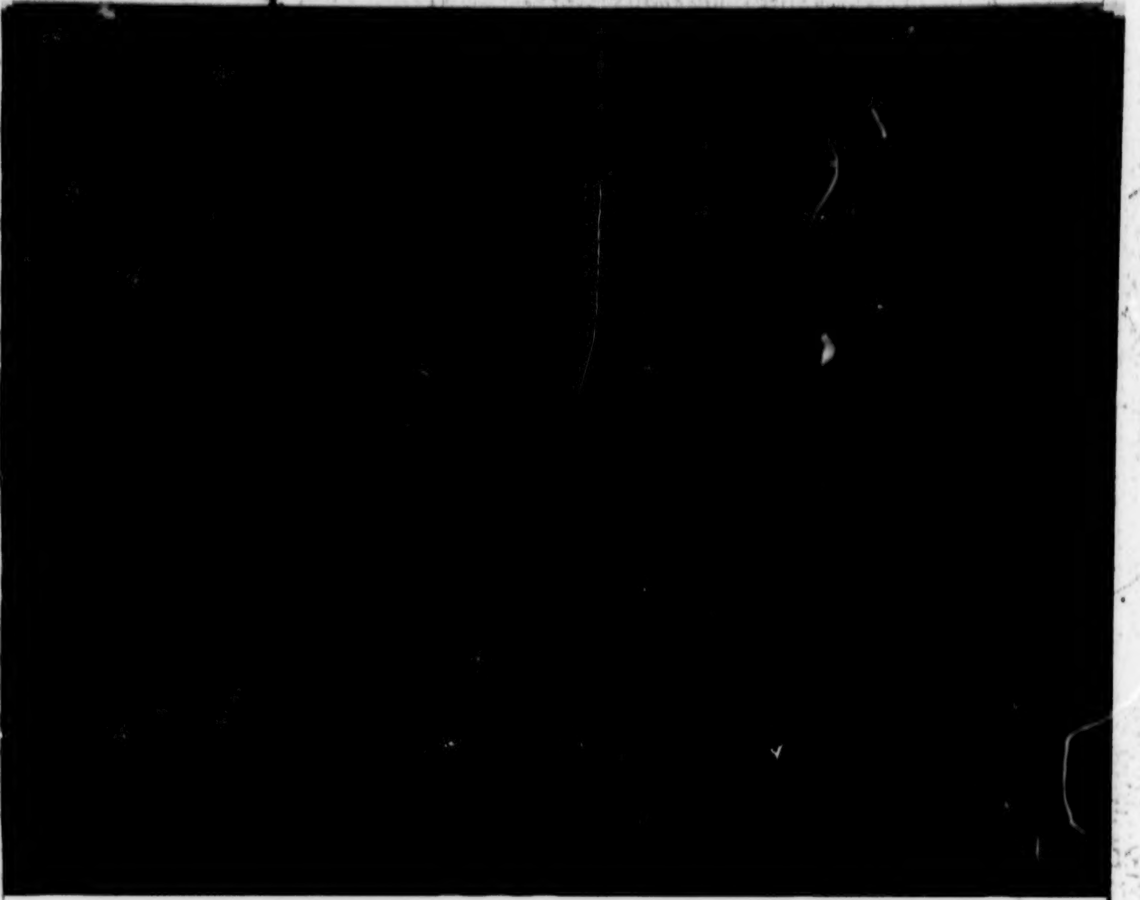
What are superbubbles? How are they produced? Where do they get their energy? The Cygnus superbubble has an unusually large number of massive stars inside it, in what is called the Cygnus OB2 association. Are they somehow responsible for the superbubble? It seems very unlikely. Observations of the energy produced in the form of radiation and "winds" of stellar gas by these and similar stars show that there are not enough stars, massive or otherwise, inside the superbubble to explain its origin. Furthermore, the stars in the Cygnus OB2 association are only about 1 million years old, whereas the superbubble must have been expanding for about 3 million years. Clearly, the massive stars did not produce the superbubble. On the contrary, we shall see later that they may have been produced by the superbubble!

What about a single giant explosion, a super-supernova? After all, we now know of stars that are over a hundred times as massive as the Sun, such as the monstrous star in the southern constellation of Carina. Could they explode and release the energy of 20 supernovas? This idea, intriguing though it might be, does not square with the facts. A super-supernova energetic enough to carve out the superbubble would produce far more X-radiation than is observed.

A more efficient method for making a superbubble is to do it a little bit at a time. As Webster Cash and Philip Charles have put it, "A dynamite blast will create a hole very quickly, but a man with a shovel can, over a longer period of time, accomplish the same goal expending far less energy." What is needed then is something intermediate between stellar winds (which is like digging a hole with a spoon — it would take too long) and a super-supernova. The obvious solution is a series of supernova explosions. But how can you get a chain reaction of supernovas? And how would they create a superbubble? A combination of careful observation and ingenious theory has led to the following rough scenario.

A giant cloud of gas, containing enough matter to make millions of stars, forms in interstellar space. Perhaps by chance, perhaps as a result of the processes that caused the formation of the cloud in the first place, one or more massive stars form in the vicinity of the cloud. As this first generation of stars ages and become giant stars, their outer layers evaporate at high speeds. This wind of stellar material pushes away the matter in the surrounding space, creating a hot bubble.

Less than a million years after entering the giant phase, the massive stars begin to explode. The blast waves from these supernova explosions rush through the bubble, inflating it and driving it at high speeds into the cloud from which the stars formed. The compression of matter along the periphery of the cloud triggers the formation of a new generation of stars. The more massive stars in this generation evolve rapidly and explode, fur-



HEAO 1 X-ray image of the Cygnus superbubble. The bright yellow and orange colors outline a giant glowing ring of hot gas that is over 1000 light years in diameter. The dark lane down the middle of the superbubble is caused by absorption from a dust lane known as the Great Rift of Cygnus. The dark spots at the lower middle and lower right are areas where strong X-ray stars appear by coincidence in the same field of view. (Courtesy Stuart Bowyer)

ther inflating the bubble, until it reaches superbubble size. The superbubble would continue to grow until it literally ran out of gas. This would happen when it reached the outer edges of the galaxy or until it collided and coalesced with another expanding superbubble. Calculations indicate that the galaxy is laced with tunnels of hot rarified gas produced by the coalescence of superbubbles. Our own solar system is apparently inside such a tunnel.

In this view, superbubbles are produced by one of the most awesome chain reactions imaginable: a chain reaction of supernova explosions. What controls it? Could it sweep through a galaxy? Given the right conditions, that is, enough gas clouds to sustain the chain, it could. Some astronomers believe that the spiral arms of galaxies are just that, a trail of stars formed in the wake of a wave of supernovas that rushed through the galaxy.

Although not everyone agrees with this method of making galactic spiral arms, there is independent evidence that the blast of supernovas can trigger star formation. Several cases have been found in which new stars are

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distributed in an arc behind an expanding cloud of matter that has evidently been shocked by a powerful blast, probably from a supernova that occurred a million or more years ago. An odd mixture of radioactive isotopes found in meteorites indicates that a blast wave from a supernova triggered the collapse some 4.5 billion years ago of the cloud that was to become our solar system.

Supernovas, then, are the explosions that drive the galactic engine forward in its evolution. Without them, the formation of stars might occur much less frequently, and the recycling of the heavy elements necessary for life might occur much more slowly.

12

STELLAR CORONAS

High energy astronomy began with observations of the Sun. The first cosmic X-rays were detected from the Sun in the 1940s, and the first X-ray telescopes were used to study the Sun as part of the Skylab Mission in 1973.

These observations of the Sun opened the eyes of the astronomical community to the potential of high energy astronomy in general and of focusing X-ray telescopes in particular. Now, with the HEAO experiments, X-ray astronomy is returning the favor. Before now, astronomers who specialize in the study of the hot outer layers of stars had only one object, the Sun, to study. Their theories as to what made the upper atmosphere or corona of the Sun so hot were frustratingly difficult to test. That has changed dramatically in the last five years. The Einstein Observatory has detected X-ray emission from the coronas of almost 200 stars of all types; the number should go over 1000 by the time all the data are analyzed.

The analysis of all the data may take several years, but it took only a few months to realize that the old theories were wrong.

Surveys using the Einstein Observatory guided by the results of HEAO 1 experiments have shown that all stars are X-ray sources at some level. The level of X-ray power from many of these stars cannot be explained by the old models for the turbulent outer layers of stars. To see why and to get some idea as to what the new results are telling us, let us take a brief look at the structure of the Sun and other stars as we understand it.

The Sun is a hot ball of gas about 1400000 km in diameter. That is, it is about a hundred times larger than Earth. The visible surface of the Sun, called the photosphere, has a temperature of about 6000° C. Above the photosphere are two layers that are best observed visually during a solar eclipse, the chromosphere, which means color sphere, because of its predominantly red color, and the corona, or "crown." Temperatures in these layers range from 4000° C at the base of the chromosphere to a million degrees in the corona. Because of the high temperature of the corona, most of its radiation is emitted in the X-ray band. Studies of the X-ray emission from the Sun and other normal stars are therefore primarily studies of the coronas of these stars.

The solar corona and now the coronas of other stars provide us with a cosmic laboratory for investigating how hot gases are produced in nature and how magnetic fields interact with hot gases to produce flares, spectacular explosions that release as much energy as a million hydrogen bombs. They also give us a means of probing beneath the surface of the star, since the production of a hot corona depends on what is happening there.

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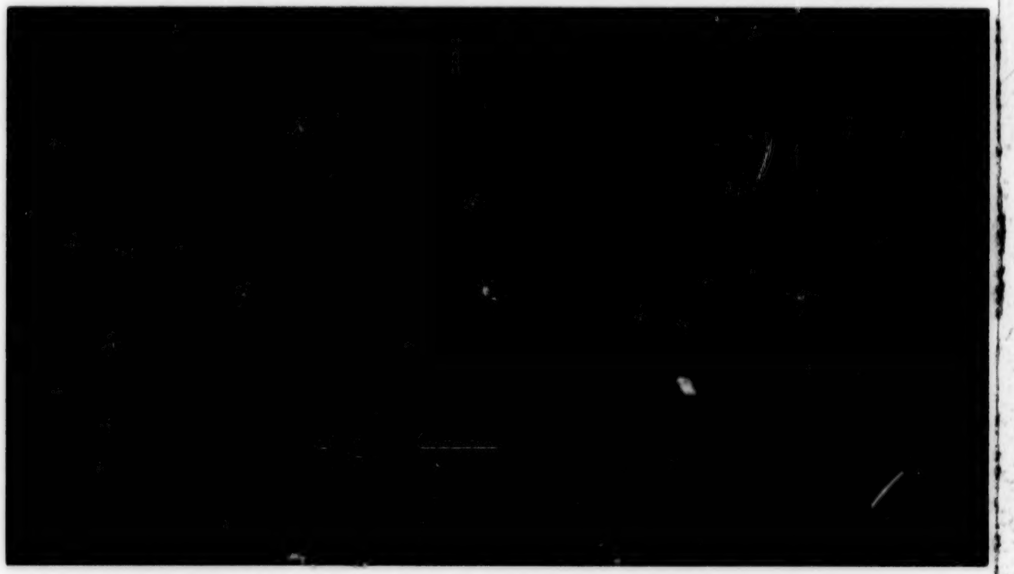

In this Einstein Observatory X-ray image of the Alpha Centauri star system, the two close companions can both be seen. The third member, Proxima Centauri, is outside the field of view shown here but is of comparable X-ray intensity. (Smithsonian Institution Photo No. 80-16240)

The energy that makes the Sun shine is generated in a huge nuclear fusion power plant buried deep in the core of the star. There, at temperatures in excess of 10 million degrees and densities exceeding that of lead, nuclear reactions are fusing hydrogen nuclei together to form helium nuclei with the release of energy. This energy gradually leaks out of the core and diffuses up toward the surface of the star.

About four-fifths of the way out from the center of the Sun, the energy can no longer be carried upward efficiently by radiation. A rolling, boiling motion does the job better. Columns of hot gas rise, transfer energy to the cooler surface gas, and descend again. Since the energy is carried upward by mass motions or convection, the region in which this occurs is called the convection zone. These motions will generate sound waves; it was suggested that the dissipation of these sound waves is the source of heat for the solar corona. Elegant theories were formulated, and many detailed calculations involving hours of computer time were performed to demonstrate the validity of this concept, which went under the general name of acoustical heating.

The accompanying figures summarize the downfall of the acoustical heating model. The X-ray photo of the Sun from Skylab shows the X-ray emission to be highly structured. Analysis of the Skylab data reveals that the X-rays come from closed tubes of magnetically confined hot gas, con-

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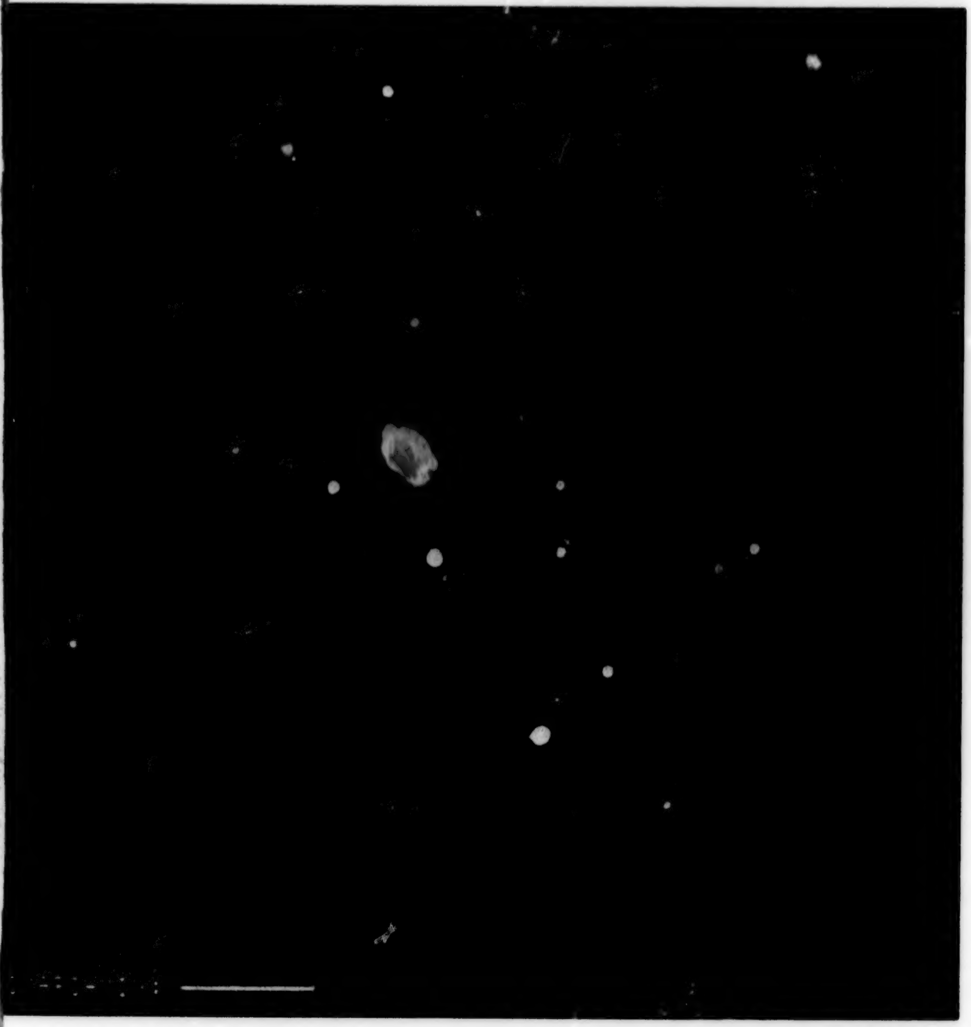


This Einstein Observatory X-ray image of the central regions of the Hyades star cluster shows a number of hot young stars that are producing X-rays. (Smithsonian Institution Photo No. 80-16241)

trary to the predictions of the acoustical heating model, according to which the corona should be a featureless fog lying above the photosphere.

X-ray photographs of star associations in the constellations of Cygnus and Carina show several sources that can be identified with stars that are much hotter and much larger than the Sun. These stars, called O stars, are not expected to have a vigorous convection zone. Therefore, they should not have acoustically heated coronas; however, they obviously have hot coronas.

Observations with HEAO 1 and 2 experiments of a number of peculiar double star systems show evidence for very hot coronas. These star systems consist of a star similar to the Sun and a cooler (K type) star that is thought to have a "starspot" analogous to, but much larger than, the sunspots on the surface of the Sun. The intensity of the X-ray emission and the temperature of the gas are both too high to be explained by acoustic heating. The temperatures are so high that strong magnetic fields, presumably near the starspot, are required to prevent the corona from evaporating.

An X-ray photograph of the Alpha Centauri star system shows that all three stars in the system have hot coronas. Visually, the system consists of a star much like our Sun (a G type star), a nearby companion K type star which is slightly smaller and cooler than the Sun, and a very small M type dwarf star, Proxima Centauri. At a distance of slightly over four light years, Proxima Centauri is the nearest star to the solar system. It is also one of the smallest stars known, having a diameter and mass less than one-tenth that of the Sun.

The acoustical heating model predicts that the G type star should be more than 10 times brighter in X-rays than the K type star, but the observations show just the opposite. The K star is the stronger X-ray source of the two.

Proxima Centauri is highly variable in X-rays. This is not surprising, since it is a flare star, as are most red dwarf stars. The surfaces of such stars are apparently covered with huge starspots over which large flares occur almost continually, producing sudden, unpredictable changes in the optical, radio, and X-radiation.

These flares are probably due to convulsions in the twisted magnetic loops of hot gas above the starspots. This is apparently what happens on the Sun, and it seems to fit for flare stars.

These examples show that the standard theory for the origin of hot coronas around stars is inadequate. It is now apparent that magnetic fields must play a key role, not just on flare stars, but in all stars. To see how this might work, we turn again to the example of the Sun.

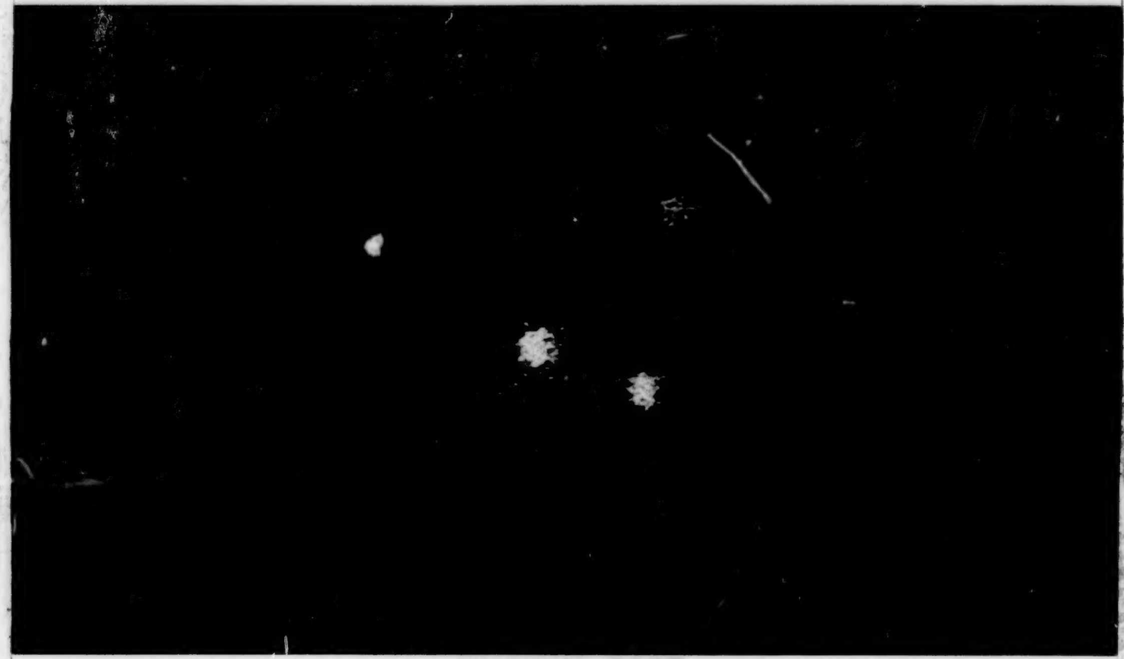
As the Skylab X-ray photograph shows, the X-ray emission from the Sun comes from groups of hot magnetized loops. What is the connection between the magnetic field and the X-ray emission? In the case of solar flares, the link is strong. A twisting or shearing of the magnetic field seems to occur before the flare.

Hours and sometimes days before a solar flare occurs, the magnetic field in a certain region is observed to be twisted and sheared into increasingly complex shapes. This twisting increases the energy stored in the magnetic field in much the same way as twisting a rubber band or a coiled spring increases the tension and the energy stored in these systems. The twisting also induces electric currents in the magnetized loops in much the same way that the rotating magnetic field in the alternator of an automobile drives an electric current to charge the battery.

(a)

Optican (a) and X-ray (b) images of the Eta Carina Nebula. Most of the X-ray sources correspond to massive young stars. (Optical view is Cerro Tololo Interamerican Observatory photo © AURA Inc.; Einstein Observatory image is Smithsonian Institution Photo No. 80-16242)

(b)



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If the loops get too twisted and the currents get too large, the system "overloads." Something analogous to a short circuit occurs, and a violent explosion rips through the stressed region, producing high energy particles, powerful blasts of radiation in all wavelength bands, and majestic prominences surging high above the surface of the Sun. This is roughly what happens in a solar flare and is probably a fair description of what is occuring on flare stars and other flaring stellar coronas.

The same general process can probably also explain the existence of hot magnetized loops on the Sun and other stars. In most cases, the twisting of the magnetic field will not be violent enough to produce a flare. The energy stored by the twisting can be converted into heat. Electric currents can do this in a manner similar to the way electric currents heat the coil on a stove top or electric heater. This heat will appear in the form of hot magnetic loops. If these loops can get rid of any excess energy by radiating it away or by conducting heat down to the cooler surface layers, then the loops will be stable and will produce a more or less steady glow in X-rays.

It appears, then, that the origin of hot coronas around stars can be traced to the twisting of magnetic fields. The strength of the surface magnetic field and the rate that it is twisted or stressed determine the intensity of the X-ray emission from stellar coronas. In turn, the field strength and the rate of twisting are probably determined by a combination of three factors: the field strength deep within the star, the structure of the convection zone, and the rate at which the star is rotating. The interaction of the boiling motion and the star's rotational motion with the deep lying magnetic field produces magnetic bubbles that float to the surface of the star, forming magnetic loops. These loops are further twisted by a combination of turbulence and rotation on or near the surface.

The strength of the magnetic field, and presumably the coronal X-ray activity, should depend on the amount of twist in the magnetic field. This should depend in some way on the number of times the star has rotated in the time it takes a bubble to rise to the surface. This is because the twisting is accomplished by dragging the magnetic field around with the rotating star in much the same way that a drop of cream is dragged out and twisted around by the rotation produced by stirring coffee in a cup.

This means that stars that are rapidly rotating and stars that have deeper convection zones should have stronger magnetic fields. Red dwarf stars, because of their small masses, are in a boiling state almost throughout their volume. Therefore, the magnetic bubbles can originate deep within these stars and can be amplified many times before they float to the surface. These stars should have enormous starspots associated with these large magnetic bubbles.

Both these effects are observed. Stars similar to the Sun that are rotating much faster than the Sun are more vigorous X-ray emitters than the Sun, and red dwarf stars are known to be covered with large active starspots.

This might also explain the observation by several groups that very young stars have X-ray emitting coronas. These stars, which are a million years old or less, are still in a state of slow collapse and are probably rotating rapidly and boiling throughout their volume.

This theory of the origin of X-ray coronas around stars is still in a rudimentary stage. Only the bare bones of a theory exist now; much fleshing out remains to be done. For now, though, the structure looks promising. It carries with it the exciting prospect of using X-ray observations to study the generation of strong magnetic fields and the interaction of these fields with matter over a far wider range than previously possible.

Finally, the verification of relatively intense X-ray emission from the obscure red dwarf stars may ultimately prove to be a most valuable discovery. Although these stars flare frequently, they are intrinsically much fainter than the Sun. This makes them very difficult to detect with even the most powerful telescopes, so not much is known about their number and distribution throughout the galaxy. In the region of space near our solar system, it is known that they are very numerous. Of the 90 nearest stars that have been classified, 62 of them are red dwarf stars.

Because of their intrinsic faintness, no one has a very good idea as to how many red dwarfs the galaxy as a whole contains. Advanced X-ray facilities should provide a powerful tool for determining just how many red dwarfs are in our galaxy and therefore how massive our galaxy really is.

An X-ray telescope aboard the Skylab satellite obtained this image of the Sun. The highly structured X-ray image is strongly correlated with regions of strong magnetic field. (Smithsonian Institution Photo No. 80-20238)

13
COLLAPSED STARS

One of the fascinations of astronomy is its continual push against the boundaries of the unknown. This can take the form of peering out across billions of light years, studying ghostly images produced by instruments strained to the limits, or it can involve pressing deep into the gravitational whirlpools surrounding stars that have collapsed to form white dwarfs, neutron stars, and black holes. High energy astronomy has led the advance here, because matter drawn into these whirlpools gives off large amounts of high energy radiation.

In collapsed stars, matter has been pushed to the limit. Internal pressures produced by nuclear power production in the centers of stars are no longer important, because the nuclear fuel has been exhausted.

As discussed in Chapter 9, a star is in a way similar to those inflatable "bubbles" that are used for indoor tennis courts or temporary structures. As long as the internal pressure is sufficient, there is no problem, but if the pressure drops drastically, the structure will collapse into a heap. The size of the heap will depend on the material that the structure is made of and how massive it is. If it is made of stiff rubbery material, it will make a fairly large heap, unless, of course, the weight of the material or material piled on top of it is so large that it squashes the material into a smaller heap.

A star, like an inflatable bubble, is held up by a balance of internal pressure against gravity. In the normal course of its life, this pressure is provided by the energy produced in nuclear reactions deep in the center of the star. When those nuclear reactions stop producing energy, the pressure drops and the star falls in on itself.

How large a heap will a star make when it collapses? The answer depends on the size of the star. A star about the size of the Sun will collapse into a heap about the diameter of Earth, or about one-hundredth the original diameter of the star. Such stars are called white dwarf stars because of their small size and because the heat generated by the collapse has made them white hot. A sphere of white dwarf material with a diameter of the size of this would weigh about two pounds, or about a hundred thousand times more than a lead sphere of the same size.

A star about five times as massive as the Sun will undergo a much more violent collapse. The outer layers of the star will be ejected into space in a supernova explosion, leaving behind a collapsed star called a neutron star.

Ordinary matter, the kind that we and everything around us is made of, is mostly empty. It is made up of atoms, which are made of electrons,

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protons, and neutrons. The protons and neutrons contain more than 99.9 percent of the matter, yet they are contained in the nucleus, which has a diameter of only 1/100000 that of the cloud of electrons around the nucleus. The electrons themselves take up little space, but the pattern of their motions, or orbits, defines a size that is the size of the atom. In a white dwarf star, the atoms are crushed to a diameter about 1/100 that of ordinary matter. Still, the matter is mostly empty. The distance between nuclei is 100 times the size of the nuclei themselves. In a neutron star, the atoms are crushed completely. The protons capture the electron clouds and are transformed into neutrons, so that most of the matter in a neutron star is neutrons, as you might have guessed.

The collapse of the core of a star to a neutron star has no analogy on Earth. It is as if a structure the size of the Empire State building were to collapse to a heap of one centimeter high! A sphere of neutron star material the size of this · would weigh about 20 million pounds, or about a trillion times more than a lead sphere of the same size.

Neutron stars represent the last stand of matter against gravity. The nuclear forces have been pressed to their limit. Stellar cores having a mass less than about three times that of the Sun can be stabilized this way. What about larger stars? Will the extra mass be thrown off in a supernova explosion, or will an unstable core be formed?

A combination of theoretical research and observation of Cygnus X-1, an X-ray star in the constellation of Cygnus, has led most scientists to conclude that the core becomes unstable.

The properties of such a core are very strange. Since nuclear forces cannot prevent gravitational collapse, the core collapses indefinitely, forming a warp in space. Nothing, not even light, can escape from this gravitational maelstrom, so the name black hole is used to describe these bizarre objects.

White dwarfs have been known to astronomers for some time. The white dwarf companion to Sirius was first observed in 1862 and explained in 1933. Neutron stars and black holes, however, are a product of modern astrophysics. Neutron stars were not discovered until 1968, and the first compelling evidence for a black hole was not obtained until 1971. Now, after a decade of highly successful high energy astronomy experiments, over 100 star-like X-ray sources have been discovered. All of these are thought to be a collapsed star of one type or another. The HEAO experiments have given us a comprehensive look at these objects. The experiments have fixed the positions of the sources, monitored the variation of the intensity of their radiation, analyzed this radiation with spectrometers, and discovered new sources.

In the following chapters we take a closer look into the strange world of collapsed stars.

14
PULSARS

The key that unlocked the door to our understanding of collapsed stars was the discovery of pulsars. In 1968, several sources of radio waves were found to be pulsing with great rapidity and astonishing regularity. They blinked on and off with the precision of a clock that loses only one second in a million years! The time between pulses varies from one object to the next, but it is typically one second or less. The most energetic pulsar is associated with the Crab Nebula, a remnant of a supernova explosion. The Crab pulsar has a pulsation period of about 1/30 of a second.

The regularity of the pulses can be understood only in terms of the rotation of a very large body, that is, a star. The rapidity of the pulsation, especially in the case of the Crab pulsar, can be explained by only one type of star – a neutron star. Any other star, even a white dwarf, would break apart if it were to rotate as fast as the pulsars must be rotating.

The rapid rotation of a pulsar is a natural consequence of the way in which they are formed. When an object collapses, any rotational motion it has is greatly amplified. A familiar example of this is the figure skater, who greatly speeds up rotation by pulling in his arms. In the formation of the neutron star, the core of a star has collapsed under the action of its own gravity to a diameter only one ten-thousandth or less than its original diameter. Since the rotational frequency increases as the square of the collapse factor, by the time the core reaches the neutron star stage, it could be rotating 100 million times faster than it originally was.

Another consequence of the gravitational collapse is that the magnetic fields tied into the core of the star are greatly amplified. A rotating magnet can produce strong electrical effects. This is the principle underlying electrical generators in automobiles, power plants, and pulsars.

Electrical potential differences of trillions of volts are produced by the rapidly rotating magnetic field of neutron stars. These voltages act to pull particles off the surface of the neutron star and accelerate them to high energies. This happens mainly near the magnetic poles of the star, producing two diametrically opposite beams of high energy particles. These particles produce beams of radiation, which, because of the rotation of the star, show up as a sequence of regular pulses. The exact mechanism for producing the beams of radiation is still not understood.

The neutron star in the Crab Nebula pulses at all wavelengths from radio to gamma rays, but it is the exception. A survey of radio pulsars with the HEAO 1 experiment detected only one pulsing X-ray source – the Crab

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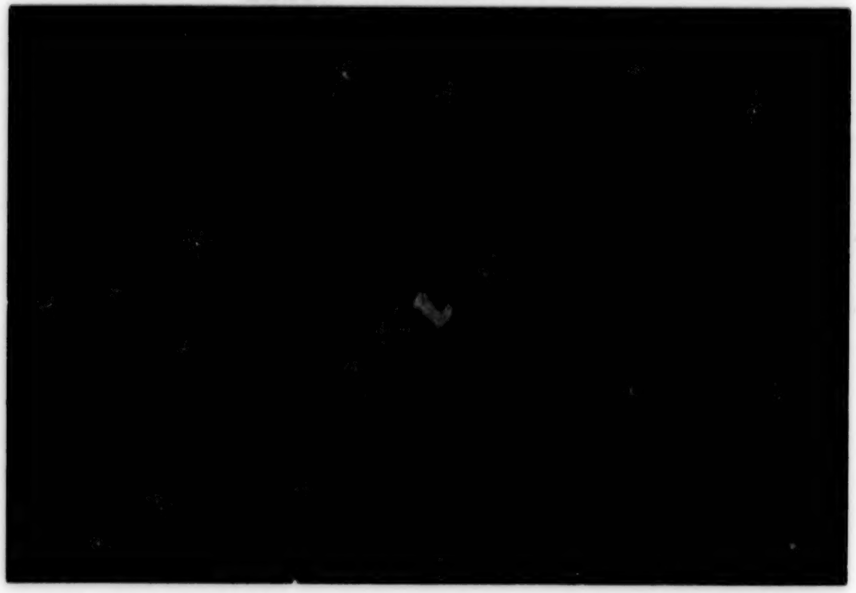

Optical image of Crab Nebula, a supernova remnant in Taurus. One of the faint objects at the center has been identified as the collapsed star left behind when the supernova occurred. This star has been observed to pulse at optical, radio, X-ray, and gamma ray wavelengths. (© Palomar Observatory)

pulsar. With HEAO 2, two pulsars have been discovered in supernova remnants. One has a pulse period of 0.15 seconds, and appears to be a system similar to the Crab Nebula. The other has a period of 3.5 seconds, more characteristic of an X-ray binary star (see Chapter 15). Recently two radio pulsars with extremely short periods, less than a hundredth of a second, have been discovered. These objects do not show pulsed X-ray emission nor are they associated with a radio or X-ray remnant. Apparently they are very old neutron stars with very weak magnetic fields. Evidently very rapid rotation and a strong magnetic field are required to produce X-ray pulses.

The discovery of pulsars proved the existence of a new type of object, the neutron star. It also showed the importance of a source of energy that had been overlooked, the energy contained in the rotational motion of the neutron star.

One of the most striking manifestations of the power of this energy source is the Crab Nebula. The Crab Nebula was produced by a supernova explosion that was observed to occur in 1054 A.D. by Chinese, Japanese, Arabian, and possibly North American Indian "astronomers." Today it is observed as a cloud that stretches across several light years and produces intense radiation from radio through gamma ray wavelengths. A careful study of the characteristics of the radiation from this cloud shows that it comes from very high energy electrons interacting with the magnetic field in the cloud.

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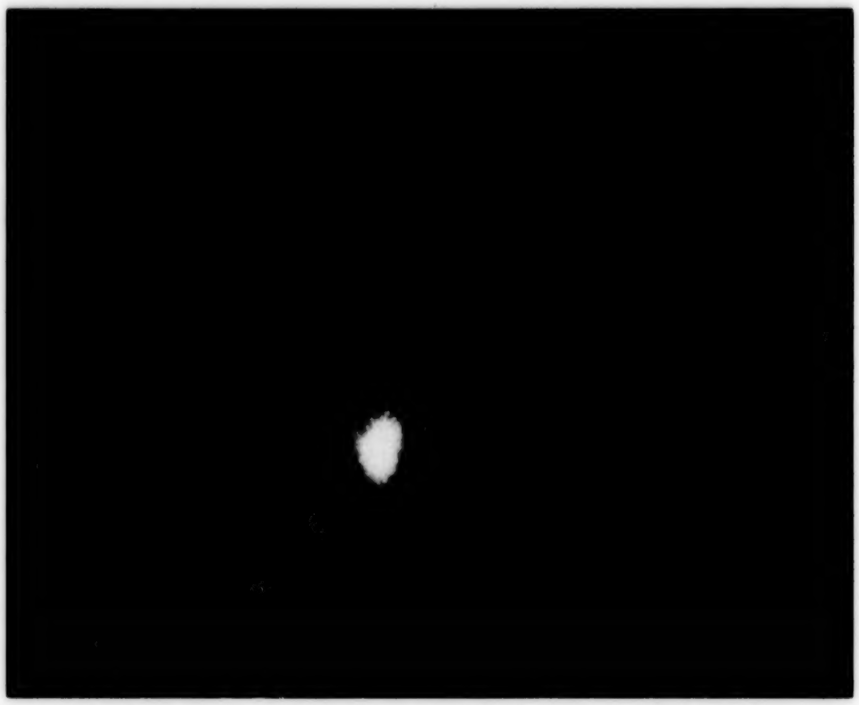
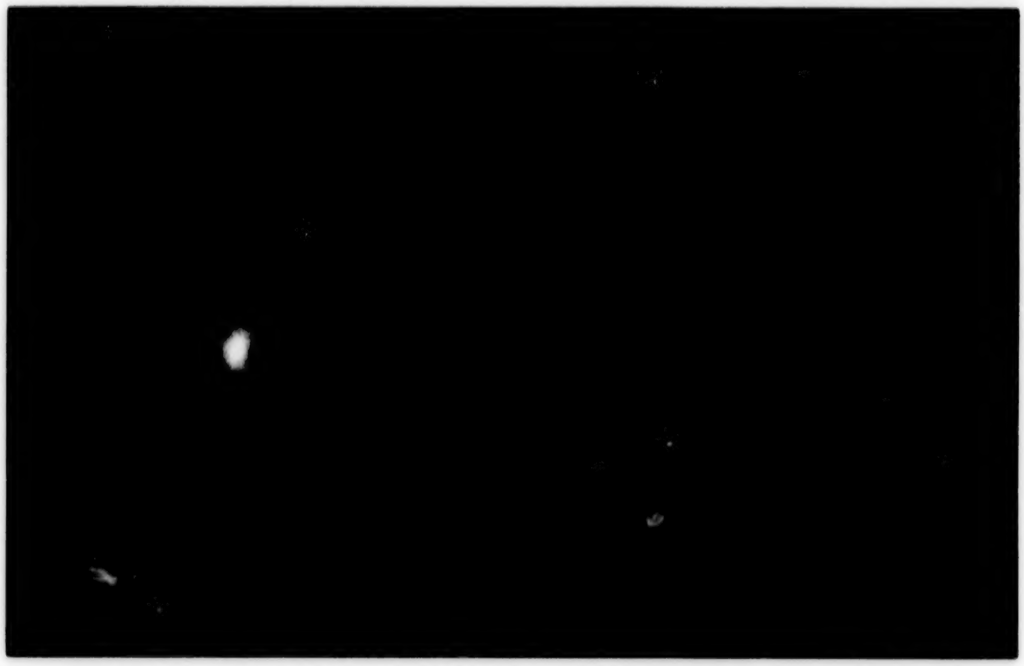
The existence of this cloud of high energy particles posed a major puzzle for astrophysicists. The particles producing the X- and gamma radiation should radiate away most of their energy in a few years or less, yet the cloud has been around for a thousand years.

The discovery of a pulsar in the center of the Crab Nebula solved the problem almost overnight. The neutron star there was spinning around 30 times a second, generating electromagnetic fields that in turn produced the high energy particles in the cloud as a whole.

The energy for the particles is coming ultimately from the rotational energy of the neutron star. If this is true, then the neutron star should be slowing down by an amount that can be estimated from the amount of energy lost in the form of radiation. In a neat check that occurs all too seldom in astrophysics, it was shown that this is indeed the case. Observations of radio, optical, and X-ray pulses showed that the pulses were gradually getting farther apart. The neutron star is slowly spinning down, with each successive spin taking about a trillionth of a second longer. Put another way, the rotational energy of the star is gradually decreasing by just the amount required.

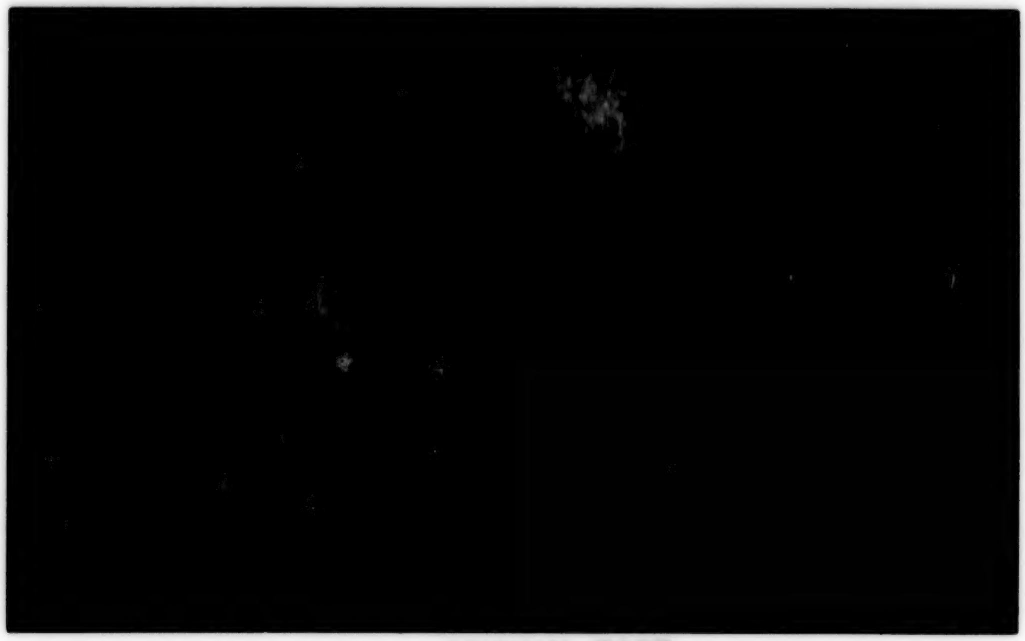


Einstein Observatory X-ray image of the Crab Nebula. In this image the central pulsar appears as a bright point. The strongest region of diffuse emission corresponds to the region of brightest optical emission. (Smithsonian Institution Photo No. 80-16233)



Stroboscopic view of the Crab Nebula pulsar. When the X-ray observations were timed to match the frequency of the pulsar, the pulsar seemed to turn on and off. (Einstein Observatory image, Smithsonian Institution Photo No. 80-16234)

Einstein Observatory X-ray image of the Vela Pulsar shows a point source surrounded by a weak and diffuse region of X-ray emission. The Vela Pulsar exhibits pulsed radio and optical emission, but no X-ray pulses have been detected. (Smithsonian Institution Photo No. 80-16237)



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Although we have a good broad brush picture explaining how the rotational energy of a neutron star is converted into high energy particles, the exact details are unknown. It is not known exactly how the particles are accelerated. Does it happen near the surface of the neutron star, where the fields are intense, or farther out, where large-scale electromagnetic waves can be effective?

The HEAO observations of the Crab Nebula will help to answer these questions. X-ray pictures made with the Einstein Observatory show the pulsar, a bright wispy region offset from the pulsar, and an overall bell-shaped nebula enveloping both the pulsar and the wisp. Comparison of these pictures with the optical and radio maps shows that the appearance of the Crab Nebula changes with the wavelength used to observe it. Since the wavelength can be related to the energy of the particles, high energy associated with X-rays, etc., this means that the high energy particles in the cloud are distributed differently from the lower energy ones. The details of the differences in these distributions tell us about the process for accelerating the high energy particles and how rotational energy is converted into particle energy. Such studies should also help us to understand high energy processes occurring on a much larger scale, in quasars and radio galaxies. These cosmic powerhouses have each poured more high energy particles into intergalactic space than a million Crab Nebulas.

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TIDES IN THE AFFAIRS OF NEUTRON STARS

Pulsars may have unlocked the door to the world of collapsed stars, but something more is needed to get inside for a better view of that world. The process by which the radio pulses are produced must be very complex, depending sensitively on details of the magnetic field and surface structure that are difficult to disentangle from the theoretical models.

The high energy pulses are a little easier to relate to the observations, but only two pulsars have been detected outside the radio band, and only one, the Crab, has been detected in X-rays. As a result, radio pulsars can give us only limited access to the realm of collapsed stars.

Other pathways to knowledge about neutron stars are available. They depend not on the rotation, but on the strong gravitational field created by the collapse. When the core of a star collapses to form a neutron star, a tremendous amount of gravitational energy is released. A similar effect occurs if you drop a book. The energy of motion gained by the book as it falls closer to the center of Earth comes from the change in the stored gravitational energy of the book. When the book hits the floor, the energy of motion goes primarily into sound and heat. In the same way, energy is released by the collapse, or infall, of a stellar core to form a neutron star. Some of this energy goes into blowing off the outer layers of the star to produce a supernova explosion. Some of it goes into energy of rotation and other forms, such as heat.

Newly formed neutron stars are expected to be very hot, with surface temperatures of 10 million degrees or more. How rapidly they cool depends on the state of the matter in the star. This will depend on the nature of the nuclear forces holding the star up, that is, on how particles interact with each other at distances of less than a trillionth of a centimeter. It is a fascinating aspect of nature that is encountered time and again: the structure of matter on a very large scale depends critically on how it behaves on a very small scale. The form of the universe and the nature of the smallest particles in the universe are tightly intertwined to form the cosmic tapestry.

Calculations based on the various theories of interactions between neutrons indicate that neutron stars formed less that 10 thousand years ago should have surface temperatures of a few million degrees. That means that they should glow primarily in the low energy portion of the X-ray band. The Einstein Observatory has surveyed a number of supernova remnants for evidence of the surface X-radiation from neutron stars. In two cases, a positive detection has been made, whereas in eight other cases no source has been detected.

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In three of the undetected objects, the lack of detection is especially bothersome. They are the remnants of Tycho's supernova, the supernova of 1006 A.D., and the source called Cassiopeia A. All these objects are less than 1000 years old, yet the neutron stars, if they exist, must have cooled well below 2 million degrees. Either the matter in the interior of the star is in an exotic, rapidly cooling state called a pion condensate, or the neutron stars are not there. On the one hand, the HEAO observations may have given us the first proof of a new state of matter. On the other hand, they may force a revision in our thinking about supernovas and neutron stars.

Until now it has been assumed that neutron stars are formed in almost every supernova explosion. A comparison of the estimates of the number of pulsars and the rate of supernova outbursts confirms this belief. Yet in the majority of remnants studied so far the neutron stars are not there.

In either event, looking for hot, newly formed neutron stars is not the most promising way to study the properties of these objects. Fortunately, there is another possibility.

If we could somehow direct a stream of particles toward a neutron star and observe the radiation produced as the particles fall toward the surface, we could learn much about the gravitational and magnetic fields on and around a neutron star. Of course, we have neither the matter nor the neutron star available to carry out this experiment. However, as is often the case in astronomy, if we can think up a cosmic experiment, we can usually find a place in the universe where that experiment is being carried out.

For neutron stars, the cosmic laboratory takes the form of a double star system. The cloud of dust and gas that collapsed to form the Sun had only enough matter to form one medium-sized star, with about a tenth of a percent left over for the planets. However, in many systems, probably over half, the protostellar cloud breaks up into two or more stars. The Alpha Centauri system is an example; it contains two stars circling around each other in an orbit about the size of the solar system, with a third star circling around these two stars at a distance of one-sixth of a light year. Another example is the double star system of Mizar in the handle of the Big Dipper. It consists of two stars separated by a distance that is about five times the diameter of the orbit of Neptune.

The stars in the Alpha Centauri and Mizar systems are so far apart that, other than causing an orbital motion around the center of mass, they do not affect each other. However, in some double star systems, the stars are so close together that they are practically touching.

The matter on the outer layers of these stars is torn between the gravitational force of the parent star holding the material to that star and the gravitational force of the companion star. As a result, the parent star can be distorted "out of round." The same sort of thing occurs on Earth. The gravitational force of the Moon pulls Earth slightly out of round, by about a foot; this distortion shows up as the high and low tides of the ocean.

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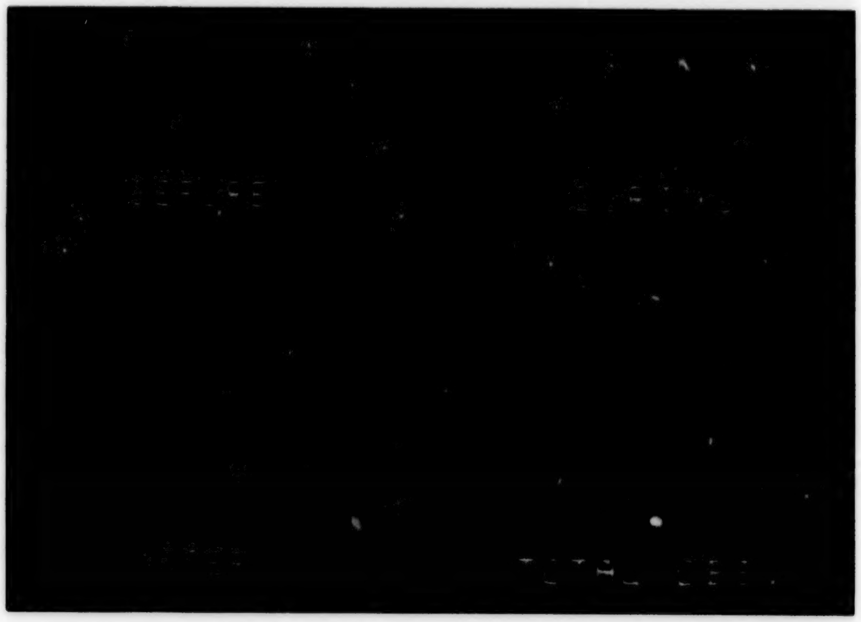
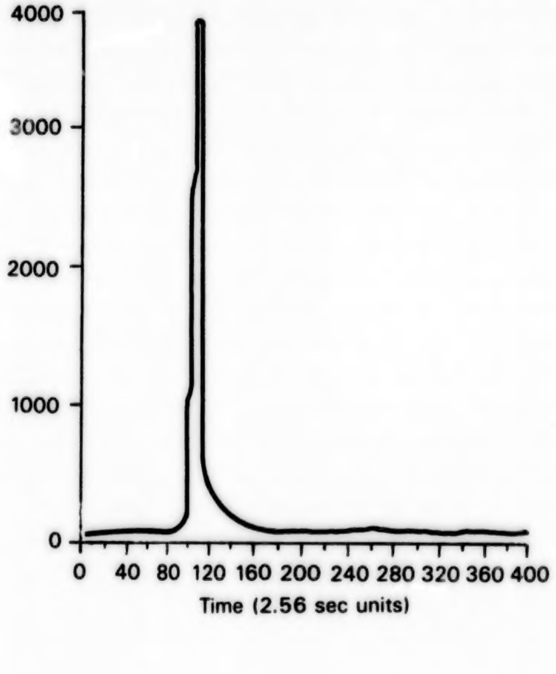


X-ray burster. This series of 2.5 minute exposures taken with the Einstein Observatory immediately before, during, and after an X-ray burst in the globular star cluster Terzian 2 shows the dramatic change in the X-ray emission that takes place during an X-ray burst. Below, the sudden variation in X-ray intensity is shown in this plot of emission over time. (Courtesy of Jonathan Grindlay)



In a similar way, one star can raise tides on another one. In extreme cases, these tides can be so great as to pull matter away from its parent star. This matter usually forms a disk around the companion star and slowly settles or accretes onto the companion.

If the companion star happens to be a neutron star, then the infalling matter will pick up a tremendous amount of energy as it falls toward the neutron star. Much of this energy will be radiated away at X-ray wavelengths, taking with it information about the conditions on or near the surface of the neutron star. Essentially the same thing would happen if the parent star had a "stellar wind" that was blowing the outer layers of the star into space. If such a star had a neutron star companion, some of the matter in the wind would eventually be captured by the neutron star, producing X-rays.

These are just the sort of experiments we wanted, and, as often happens, nature provides them for us. Several hundred strong starlike sources have been discovered. Many of the X-ray stars that have been studied in detail have turned out to be systems of the type discussed above: neutron stars accreting matter from a nearby distended companion star.

Accreting neutron stars are, in a way, the opposite of radio pulsars. Matter is drawn onto the surface of the star instead of being expelled from it, and the star's rotation speeds up instead of slowing down. This happens because the material spirals in with the same sense of rotation as the neutron star, so it adds to the star's rotational energy. The two objects are opposite in that radio pulsars are seldom X-ray sources, whereas X-ray pulsars are seldom radio sources. The radio pulses from an X-ray source are presumably quenched by the high density of infalling matter.

In two important respects, many X-ray stars and radio pulsars are similar. They are both neutron stars, and they both produce periodic pulses of radiation. In both cases, the magnetic field is responsible for the pulses. It provides a channel for the outflowing matter in the radio pulsar. For X-ray stars, the magnetic field acts as a funnel to guide the infalling matter down onto a localized hot spot on or near the surface of the neutron star. As the star rotates, this hot spot comes into view once every rotation period, producing an observed pulse of X-rays about once a second.

High energy observations of the details of the radiation from X-ray pulsars have provided the first direct measurement of the magnetic field strength near the surface of a neutron star. It is several trillion times as strong as the magnetic field on Earth and several hundred thousand times stronger than the strongest magnetic field ever produced in a laboratory.

The regular pulses produced by X-ray pulsars provide astrophysicists with an extremely useful tool. In essence it gives them a clock. By studying the variations in the time kept by the clock, they can extract information about the motion of the clock, the forces acting on it, and the structure of the clock itself.

For example, the pulsar is in orbit around the companion star. This orbital motion will cause the clock to appear to speed up when it is moving toward our line of sight and to appear to slow down when it is moving away from us. From a careful study of this apparent speeding up and slowing down of the pulses, the motion of the pulsar can be deduced. When these observations are combined with observations of the motion of the companion star and observations of the eclipses of the X-ray pulsar by the companion star, the masses of the stars can be obtained.

Results obtained in this way represent the only reliable mass measurements of neutron stars. An exhaustive study of this type shows that the masses of neutron stars in the seven systems investigated so far are most probably in the range of 1.2 to 1.6 times the mass of the Sun. This is in good agreement with theoretical calculations of the expected mass of a neutron star and represents a major confirmation of the theoretical ideas concerning collapsed stars.

Not all of the X-ray stars are pulsars. Some of them are observed to give off a steady glow of X-radiation; others give off energetic bursts of X-rays. These latter sources, which are called X-ray bursters, give off as much X-ray energy in a few seconds as the Sun radiates at all wavelengths in two weeks. These bursts occur sporadically at intervals ranging from several hours to a few days.

A combination of detailed observations and theoretical work by many researchers has shown that these bursts are most probably caused by thermonuclear flashes on neutron stars in double star systems.

Like the X-ray pulsars, the bursters are powered by the infall of matter onto a neutron star from the companion star. The infalling material is primarily hydrogen, the most common element in the universe. The surface of the neutron star accumulates a coating of hot dense hydrogen that is about ten feet thick.

Except for the high magnetic field, the conditions in this shell are not too different from those in the center of the Sun, where the hydrogen undergoes nuclear fusion reactions that convert the hydrogen into helium.

On Earth, helium is known for being a safe, stable element that will not burn. On the surface of a neutron star, the opposite is the case. The sticking together or nuclear fusion of helium nuclei to produce carbon nuclei requires temperatures of about 100 million degrees to work, but when it works, it works with a bang. A violent thermonuclear flash, much like what happens inside a nuclear bomb, is the result. An enormous amount of energy is released, heating the surface of the neutron star to temperatures of 15 million degrees. The hot surface glows for a few seconds, producing a burst of X-rays.

Apparently, sources that produce X-ray pulses do not burst, and sources that produce X-ray bursts do not pulse. The underlying reason for this is probably the magnetic field strength on the surface of the neutron star. If the field is strong, the infalling matter is channeled onto a small area. The strong magnetic field and the concentration of the matter at the base of the magnetic poles tend to make the nuclear fuel burn steadily rather than in bursts.

X-ray bursters are a spectacular illustration of the energy-generating capabilities of accreting neutron stars, but even more astounding variations on the theme no doubt exist. One may be the source known as SS433. This fantastic object is spewing two narrow high-speed jets of matter in opposite directions. A large, diffuse radio and X-ray emitting cloud not unlike a supernova remnant surrounds the jets. The power needed to maintain these jets, which are moving at about a quarter of the speed of light, is several hundred thousand times the power produced by the Sun every second.

At the heart of the object is a double star system and an X-ray star. This has led to the suggestion that SS433 is an accreting neutron star gone beserk, producing so much energy that it blasts a hole in the accretion disk, producing a twin exhaust jet structure. Why is SS433 so different from other X-ray stars? No one is sure. One possibility is that it is a hybrid object, producing energy through rotation, as in the Crab Nebula pulsar, and accretion, as in normal X-ray stars. Another is that the rate of flow of gas onto the collapsed star is extraordinarily large, producing an unstable disk that explodes into the exhaust jets. Finally, the central object may not be a neutron star at all, but a massive black hole, pulling matter in at a supercritical, or unstable rate.

Whatever the answer, the data accumulated on SS433 and many other observations around the world will be studied intensively in the years to come. SS433 has a striking resemblance to other, much larger jets produced by violent radio galaxies and quasars. It could serve as the codex that reveals the secrets of some of the most enigmatic objects in the universe.

16

DEGENERATE DWARFS

Someday the Sun will run out of fuel. According to the projections of astrophysical theory, this will happen in about five billion years, and the Sun will turn into a degenerate dwarf star. Nuclear fusion reactions in the central parts of the Sun supply the energy that keeps the Sun shining. The raw material for these reactions is hydrogen gas. When the hydrogen in the central parts of the Sun is used up, the Sun will have a brief career as a red giant star. During this time the core of the Sun will collapse; a shell of hydrogen gas on the edge of this collapsed core will be compressed and heated by the collapse of the core. Thermonuclear reactions involving the fusion of hydrogen nuclei and helium nuclei will produce a new surge of power in the central regions of the star. The outer layers of the Sun will expand until the Sun has a diameter a hundred times its present value. The oceans will boil and the mountains will melt. Then, in a few hundred million years, the shell of hydrogen gas will be used up, and the Sun will collapse to form a white dwarf star about the size of Earth. When this happens the Sun will be at most a few percent as bright as it now is.

White dwarfs were the first type of collapsed star to be discovered. In the nineteenth century, the German mathematician and astronomer Frederick Bessel concluded from the wobbly motion of the bright star Sirius that it must have a nearby companion star with a mass about equal to that of the Sun. Shortly thereafter an American astronomer, Alvan Clark, found the dim companion to Sirius. It was called Sirius B. Sirius B was found to have a mass about equal to that of the Sun, as expected. However, its luminosity is only about 2 percent that of the Sun. The luminosity of a star depends on its surface temperature and its diameter. The abnormally low luminosity of Sirius B can be explained by assuming that Sirius B has a very low temperature or a very small diameter. The temperature was found to be even higher than that of the Sun; thus, the inescapable conclusion is that Sirius B has a diameter of only about a hundredth of that of the Sun. Because of the white color of the star, it was called a "white dwarf" star. This was an extraordinary discovery. It meant that the same amount of material contained in the Sun is packed into a volume one millionth the size of the Sun. The density of material in Sirius B must be a million times denser than that of ordinary matter. That is, a cubic centimeter of Sirius B matter has the same mass as a small automobile!

How such a state of matter could exist was beyond the understanding of physicists until a new theory of matter, quantum mechanics, was developed in the 1920s. This theory showed that matter can exist in so-called "degenerate" states of extremely high density.

Even though the degenerate state of matter cannot be produced in a terrestrial laboratory, it is very common in the universe at large. Almost all of the mass of white dwarfs is in the form of degenerate matter, and most stars eventually become white dwarfs, or degenerate dwarfs, as they are also called. It has been estimated that there are a billion or more degenerate dwarfs in our galaxy. Despite their ubiquity, the study of degenerate dwarfs remains a difficult business, because they are so dim. A degenerate dwarf gives off at most a few percent as much optical radiation as does a star such as the Sun; most of them give off much less. X-ray observations have provided an important new method for studying degenerate matter. A few degenerate dwarfs, such as Sirius B, are still sufficiently hot that they give off detectable fluxes of X-rays. On the whole, however, as with neutron stars, the most favorable conditions for observing degenerate dwarfs occur when the degenerate dwarf is accreting matter from a nearby companion star. Sirius A is too far from Sirius B to be an effective source of matter, so this process does not work for Sirius B. However, it does for many other star systems. As a result of the HEAO programs, about 50 degenerate dwarf X-ray sources have been observed.

The details of the X-ray production by an accreting degenerate dwarf depend on several factors, such as the mass of the degenerate dwarf, its rate of rotation, its surface magnetic field, and the rate at which matter is supplied to the star. By disentangling these effects through careful observation and theory, the properties of the star and the physical conditions on the surface of the star can be deduced. For example, the analysis of the HEAO observations of the degenerate dwarf star AM Hercules shows that the mass of the star is about 70 percent that of the Sun, and the radius is about one-hundredth that of the Sun. That is, the star is about the same size as Earth. AM Hercules is apparently locked in synchronous rotation with its companion star. In other words, as AM Hercules orbits around its companion, it always keeps the same face toward it, just as the Moon always keeps the same face toward Earth.

The accreting gas apparently flows in a steady stream from the companion star toward AM Hercules. Near the star it is funneled toward the magnetic pole by the strong magnetic forces there. As the gas is drawn near the surface of the degenerate dwarf, it falls ever faster because of the increasingly strong gravitational forces. Eventually a shock wave is produced, heating the material to very high temperatures, producing an intense source of X-ray emission.

The conditions in X-ray emitting gas around AM Hercules are remarkably similar to those needed to make fusion reactors on Earth work. The temperature is several hundred million degrees in both cases, the density is about the same, and the magnetic field strengths are similar. Of course, there are important differences. The strength of the gravitational field and the overall size of the heated region are much larger on the degenerate dwarf. Nevertheless, detailed studies of degenerate dwarf X-ray sources should sharpen our understanding of processes that occur in high temperature gases, as well as the degenerate state of matter.

In some degenerate dwarf X-ray sources, the matter apparently falls onto the star erratically, in clumps, producing irregular bursts of X-ray and optical radiation. Regular X-ray pulses have been observed during these outbursts. These pulses could be associated with oscillations in the flow of matter onto the surface of the star, or they could be associated with vibrations of the surface of the star. This last possibility would be particularly exciting. Just as the study of vibrations on Earth produced by earthquakes reveals the interior structure of Earth, so could studies of X-ray pulsations tell us about the interior of white degenerate dwarfs. The studies of the X-ray pulses from degenerate dwarf sources are just beginning, but with the data accumulated by the X-ray "eyes" of the HEAO instruments, we may eventually be able to "see," albeit indirectly, inside a degenerate dwarf.

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BLACK HOLES

The most captivating object yet to be discovered in high energy astrophysics is not a white dwarf or even a neutron star. It is the black hole. Black holes have gripped the imagination of scientist and layman alike. The reason is clear. In a world where absolutes are few and far between, the black hole gives us an absolute. It represents gravitational collapse without limit. According to physics as we know it, the matter that falls inside a black hole never escapes. It collapses forever. Because of their extreme nature, many scientists have rebelled against the notion of black holes. Other, as yet unknown effects must intervene to prevent the formation of black holes, they maintain. Nature would somehow not allow such an extreme situation to develop.

Yet nature apparently does allow it. Combined radio, optical, and X-ray observations have produced an object that looks the way we think a black hole should look. This object is in the constellation of Cygnus. It is called Cygnus X-1 because it is the strongest X-ray source in Cygnus. Before discussing the evidence for believing that Cygnus X-1 is a black hole, consider briefly what a black hole is expected to look like. The theory of stellar evolution predicts that at a certain critical time, when the core, or central parts, of a star has used up its nuclear fuel, the core will collapse. If the star is about the size of the Sun, it will turn into a degenerate dwarf star. If it is somewhat larger, it may undergo a supernova explosion that leaves behind a neutron star, that is, a star in which gravitational forces are held in check by nuclear forces. But if the stellar core has a mass greater than about three solar masses, gravitational forces overwhelm nuclear forces and the core collapses. Since nuclear forces are the strongest repulsive forces known, nothing can stop the continued collapse of the star. A black hole in space is formed. We would expect, then, that a black hole would have a mass greater than three times the mass of the Sun.

The next bit of information comes from Einstein's gravitational theory, which tells us what the conditions must be like around a black hole. First of all, the theory tells us that black holes give off no detectable light or radiation of any kind. Because of the intense gravitational forces near the black hole, nothing can escape from it, not even light, which moves at 300 000 km per second. If we were to send a probe toward an isolated black hole, the probe would detect no radiation from the black hole. It would, however, sense a gravitational field, because the black hole has mass. As long as the

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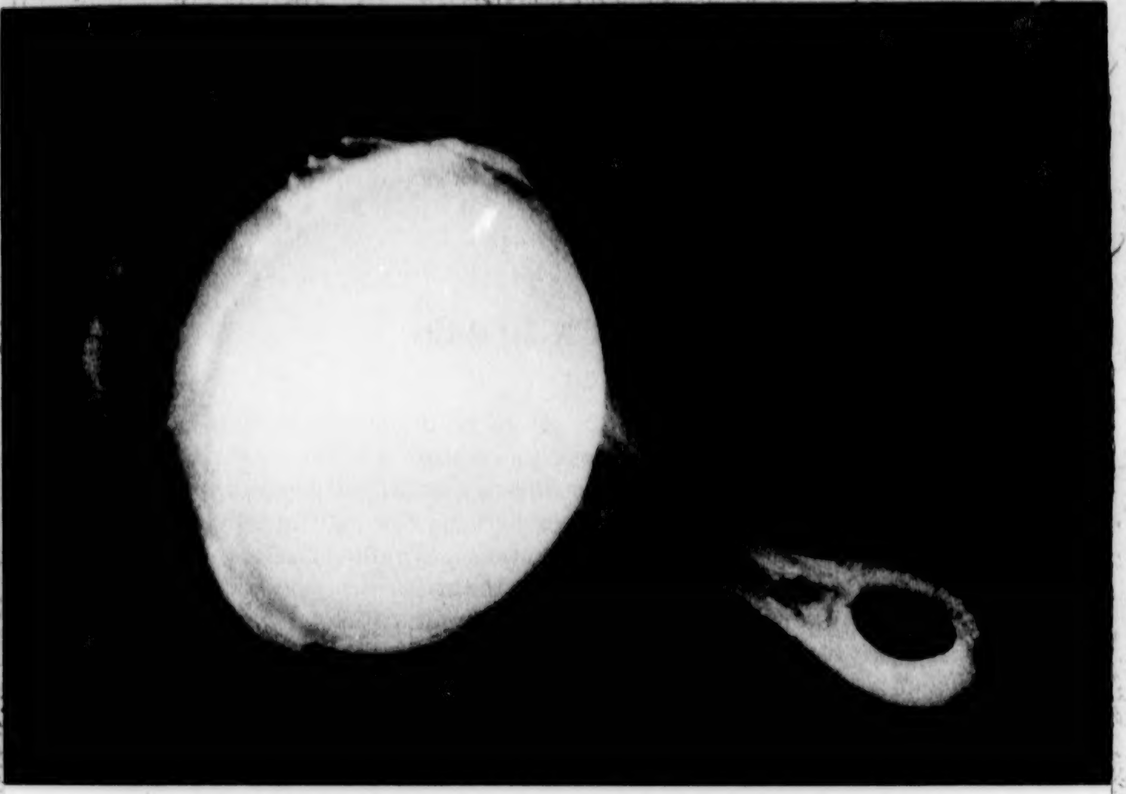

Black hole model for Cygnus X-1. Matter from a supergiant companion star is pulled away from the star by the gravitational field of the black hole. This matter forms a gaseous disk around the black hole. As the gas swirls into the black hole, it is compressed and heated to very high temperatures, producing a strong flux of X-radiation. (Painting by Lois Cohen)

probe were a safe distance away, say a few million kilometers, the gravitational field it sensed would be no different from the gravitational field produced by a normal star of the same mass. The only difference would be that no star would be visible, even though the probe could sense the presence of a large concentration of matter through the gravitational forces. At this point the probe could still escape from the gravitational pull of the black hole, if we could give it a boost of energy from a rocket, for example. Suppose, however, that we chose to send the probe closer.

As the probe approached the black hole, the gravitational forces would increase inexorably. At a distance of a few thousand kilometers from the black hole, the gravitational forces on the probe would be so great that the side of the probe closest to the black hole would literally be torn away from the side furthest away from the black hole. Eventually, at a distance of a few kilometers from the black hole, the particles that made up the probe would pass the point of no return. No matter how much energy we gave these particles, they could not escape. The gravitational forces are simply too strong. The particles would be lost forever down the black hole. This point of no return is called the gravitational radius of the black hole. For a black hole containing about 10 times the mass of the Sun, the gravitational radius is about 10 km. An observed concentration of more than three solar

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masses inside a region having a diameter of a few tens of kilometers would be very strong evidence for a black hole. But how can we hope to observe such an object, since black holes give off no detectable radiation? By sending in probes, or test particles.

As in the case of neutron stars and degenerate dwarfs, nature could provide us with a probe of a black hole. All that would be required is a nearby star that is losing mass into the black hole. As this matter swirls into the gravitational maelstrom produced by the black hole, it will send back information, in the form of radiation, about conditions near the gravitational radius of the black hole. Of course, it cannot send back information about conditions inside the gravitational radius; the radiation cannot escape from inside the radius. As the matter of the companion star spirals toward the black hole, it will move faster and faster. This increased energy of motion will be changed into heat energy by dissipative processes — a sort of friction — in the stream or disk of infalling matter. Near the gravitational radius the matter will be swirling around at speeds close to the speed of light, and temperatures ranging from tens of millions to perhaps as much as a billion degrees are expected. At these temperatures, X and gamma radiation are produced. A black hole in a double star system would therefore be expected to be a strong source of X and possibly gamma rays. Furthermore, since a blob of matter near the gravitational radius would be orbiting the black hole about once every millisecond, the X-radiation might be expected to show erratic, short-term variability. The variability in the X-radiation is not expected to show any regular or periodic behavior such as is often observed with neutron stars and degenerate dwarfs. Unlike these objects, the black hole has no strong magnetic field to guide the matter in a preferred direction.

To summarize, then, a black hole that is part of a close binary system should show evidence of a mass greater than three solar masses concentrated into a small area, and it should be a strong source of X-radiation. The X-ray source Cygnus X-1 meets all these requirements. It is part of a binary star system in which a blue supergiant star is orbiting an invisible companion star. This invisible companion star has a mass greater than about nine times the mass of the Sun. It is a strong X-ray source that shows rapid time variations in the intensity of its X-ray flux. Because of the good fit between what is expected and what is observed, and more importantly, because they can think of no other object that could meet the requirements described above, most astronomers believe that Cygnus X-1 is a black hole. This belief is tempered with a dose of caution, however. In most scientific papers describing Cygnus X-1, it is referred to as a black hole "candidate" rather than simply as a black hole; somehow, the concept of a black hole is still a little difficult to swallow.

The HEAO instruments have been used to perform an exhaustive study of the spectrum and time variability of the X-radiation from Cygnus X-1. The goal is to establish in detail the X-ray properties of Cygnus X-1 and to use these results to better understand the state of matter near the gravitational radius of a black hole. The HEAO 1 results indicate that there is a distribution of temperatures in the hot gas around the black hole; these temperatures range from 30 million degrees to about a billion degrees. A study of the variability of the X-radiation indicates that a variation in the high energy photons typically occurs about 10 milliseconds later than a variation at a slightly lower energy. This could mean that the higher energy photons take slightly longer to get out of the source. Measurements such as these, when coupled with theoretical analysis, will help greatly to determine the physical state of the gas around the black hole.

They should also help to provide a definite X-ray signature for a black hole. This would be of great help in the search for other black holes in our galaxy. Recently, another strong black hole candidate has been discovered. A team of Canadian and American astronomers have used optical observations and results from HEAO 1 and the Einstein Observatory to show that the strong, highly variable X-ray source LMC X-3 in the Large Magellanic Cloud (a nearby galaxy) is associated with a dark star with a mass greater than nine solar masses. Since this mass far exceeds the upper mass limit of three solar masses for neutron stars, this object is also a strong candidate for a black hole. Two other sources, known as Circinus X-1 and GX 339-4, show rapid and erratic time variations that are similar to those observed for Cygnus X-1. However, unlike Cygnus X-1, these sources show no evidence of very high temperature (hundreds of millions of degrees) gas. Both the sources are known to be members of a close binary system, but it has not been possible to determine the mass of the X-ray source in either case. Both objects could be neutron stars.

Another location in the galaxy at which a black hole has been suggested to be lurking is the center of the galaxy. This black hole would have been formed, not from a single massive star, but from hundreds of thousands of massive stars, or from a supermassive star. It would have a mass of a million times or more solar masses. Some scientists believe that a supermassive black hole is at the center of virtually every galaxy and is responsible for violent activity that is so characteristic of the central regions of galaxies.

18

THE REALM OF THE GALAXIES

One of the beauties of astronomy is that you do not have to be an expert to enjoy it. Anyone can step outside on a clear moonless night, gaze at thousands of stars shining across the vast interstellar spaces, and become intoxicated by a heady mix of grandeur and existential chill. The same questions come to mind time and again: How far away are the stars? How many are there? Are they strewn endlessly through space, or are we part of an island universe of suns that ends abruptly somewhere out there in the black ocean of space? It has been the sometimes heroic and often frustrating task of astronomers since the dawn of science to chart our position in the cosmic ocean. In the twentieth century, significant progress has been made in constructing an accurate map of the cosmos.

We know, for example, that our solar system is part of a much larger system of hundreds of billions of stars. This system is the Milky Way Galaxy, a huge disk of stars and gas. We also know that ours is not the only galaxy in the universe. As far as the largest telescopes in the world can see, there are galaxies in every direction. The nearest galaxies to our own are the Magellanic Clouds, the "crown jewels of the southern skies," to use Bart Bok's description. The Magellanic Clouds are small irregular galaxies, a catch-all term for those somewhat shapeless galaxies that do not fit neatly into a spiral or elliptical category. The Large Cloud is about 160000 light years from the solar system and has a mass about one-tenth that of the Milky Way Galaxy. The Small Cloud is about 200000 light years away; it has a mass about one-thirtieth that of the Large Cloud. Because they are so near, they are an invaluable laboratory for astronomers to study the evolution of stars and galaxies. The nearest large galaxy to the Milky Way Galaxy is the Andromeda Galaxy, at a distance of about 2 million light years. It is a giant spiral galaxy, much like our own in size, shape, numbers of stars, and types of stars. This nearby sister galaxy provides us with an opportunity to get a bird's eye view of a galaxy much like our own, to, in effect, "see ourselves as others do."

Just as stars are bound together by their gravitational forces to form galaxies, so also do galaxies come together to form groups or clusters. Our galaxy and the Andromeda Galaxy, together with at least 19 smaller galaxies, form a complex called the Local Group. The Andromeda Galaxy and the Milky Way Galaxy are at opposite ends of the group. The smaller galaxies are clustered around the larger ones, but on the whole, there is a lot of empty space in the group, and the chance of the large galaxies ever colliding is remote.

As we look beyond the Local Group to distances of a few tens of millions of light years, we find other similar groups of galaxies. At a distance of about 60 million light years, in the Virgo constellation, we encounter the Virgo cluster of galaxies. The Virgo cluster is a system of several thousand galaxies. Most of these galaxies are large spirals and smaller, elliptically shaped galaxies. In addition, it contains a few giant, spherical galaxies. About 10 percent of all the galaxies in the universe are in rich clusters such as Virgo. One especially rich cluster is located in the constellation Coma Berenices. Called the Coma cluster of galaxies, it is almost directly overhead in the springtime sky, about 400 million light years away.

In the Coma cluster, 1000 galaxies are packed into a space roughly the size of the Local Group, which contains only about 20 galaxies. The crowded conditions in the Coma cluster and other rich clusters of galaxies have undoubtedly played a dominant role in the evolution of the individual galaxies and the cluster as a whole. X-ray observations have revealed that the space between the galaxies in rich clusters is filled with hot gas. As the galaxies move through this gas, they are stripped of gas and dust, adding to the supply of cluster gas. At the same time, this process deprives the galaxies of the raw material from which to form new stars. In a sense, then, galaxies age more quickly in the congested environment of rich clusters, because new generations of stars cannot form.

The galaxies in clusters show other peculiarities. An example is the giant elliptical galaxy known as M87. This remarkable galaxy is located in the center of the Virgo cluster. It is about three times more luminous than our galaxy and is estimated to contain as many as a trillion stars. Emanating from the nucleus, or central region of M87, is a peculiar jet-like feature. This jet is a strong source of radio, optical, and X-ray emission. Evidently, the jet was ejected from the nucleus of M87 a million or so years ago in a violent explosion that may still be occurring today.

In the last 20 years, evidence of explosive activity has been found to be a common feature of many elliptical galaxies and other peculiar objects, most notably quasars. In fact, virtually every galactic nucleus is the site of explosive activity at some level. In quasars, these explosions are awesome. An energy output exceeding that of 10 trillion suns is produced in a region approximately the size of our solar system! It is as if a power source the size of a small flashlight could produce as much light as all the lights in metropolitan Los Angeles.

What is the source of the violent activity in the galactic nuclei and quasars? Many intriguing ideas – multiple supernova explosions, supermassive stars, huge spinning magnetized disks of gas – have been suggested, but the one that is being taken most seriously nowadays involves black holes having the mass of hundreds of millions of suns. The basic idea is the same as that discussed in the previous chapter. As matter falls toward a black hole, it gains a tremendous amount of energy. If only a small fraction of this energy, say 10 percent, is radiated away before the matter falls into the black hole, and if there is a steady supply of infalling matter, then a large amount of energy can be radiated from a very small region of space. For the most powerful quasars, roughly one solar mass of material would have to fall into the black hole every year. In this picture, a quasar is a more or less ordinary galaxy with an extraordinarily active black hole in its nucleus.

Because of their high luminosity, quasars can be seen at great distances – 10 billion light years or more. That is, the light, radio waves, and X-rays we now see from the most distant quasars left those objects more than 10 billion years ago. That is about the time that most astronomers believe the galaxies were forming. The observations indicate that quasars were considerably more numerous then. This raises the suspicion that the quasar phenomenon may be intimately related to the process of galaxy formation. In any event, quasars are proving to be extremely valuable beacons with which to illuminate the frontiers of the cosmic ocean. The questions raised by the observations of clusters of galaxies and the explosive galactic nuclei are at the frontier of modern astrophysical research on the structure and evolution of galaxies and the universe. Observations made in the high energy band of the spectrum, especially those made with the sophisticated HEAO instruments, have played and are still playing a vital role in pushing back this frontier and enlarging our perspective of the universe in which we live. In the next few chapters, I touch on some of the results from the HEAO experiments and how they relate to some of the outstanding cosmologic questions of the day: How do galaxies evolve, both inside and outside of rich clusters of galaxies? What is the nature of the hidden mass that holds clusters of galaxies together? What causes the explosive activity in galactic nuclei and quasars? Is there matter between the clusters of galaxies? Is the universe finite or infinite?

19

X-RAY IMAGES OF GALAXIES

It is one thing to know that bizarre objects such as neutron stars and black holes exist. Quite an impressive thing, in fact, when you consider that until less that 20 years ago, both objects existed only on paper, the products of the fertile minds of a few theoretical physicists. Now we have convincing proof that neutron stars exist and very strong evidence for black holes. Furthermore, thanks to space observatories such as the HEAOs, we can study the properties of individual neutron stars and black holes in detail. We can also take the next step, that is, to study how these objects fit into the overall scheme of things. To do this, we must take a galactic view, because the galaxy is the stage on which the drama of stellar evolution is acted out.

The difficulty of this approach is that we are part of the galaxy; we are on stage, too, so it is not easy to get an overall view of things. Nevertheless, thanks to the HEAOs, we can construct a broad-brush X-ray picture of our Milky Way Galaxy. It contains at least one black hole candidate, Cygnus X-1, and about 30 other high luminosity sources that are most likely associated with neutron stars. These sources radiate a thousand or more times as much energy in X-rays as the Sun radiates at all wavelengths. About half of these high luminosity sources are associated with young massive stars that supply the stream of gas that falls onto the neutron star to produce the X-rays. Since massive stars evolve much more rapidly than low mass stars, these sources should be associated with regions containing young stars, such as spiral arms. This appears to be the case. The other high luminosity sources are associated with older stars that have masses similar to that of the Sun or less. These sources are associated with an older galactic population. They are found mostly in the central bulge of the galaxy and in tight clusters of old stars called globular clusters. Also prominent in the X-ray picture of the galaxy are the remnants of supernova explosions. Two dozen or more of these sources are scattered throughout the galaxy. They show up primarily as bubbles of hot gas, although at least in four cases, a bright neutron star pulsar shines in the center of the remnant. At much lower luminosities, hundreds of thousands of times dimmer than the bright sources, the degenerate dwarfs show up. Still fainter are the X-rays produced by billions of normal stars. Finally, there is an X-ray and gamma ray source that is associated with the nucleus of the galaxy. The luminosity of this source is comparable to an average bright source of the type discussed above, but it must be of an entirely different nature.

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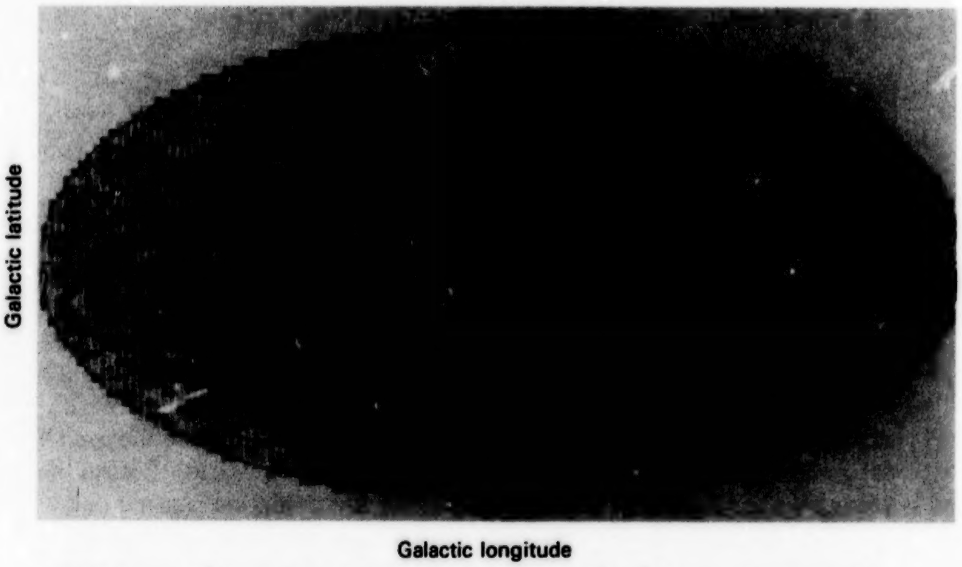
HEAO 1 A-2 HEDI, 2-60 keV, (6° + 3°) X3° FOV

HEAO 1 map of the surface brightness of the X-ray sky. The map is presented in galactic coordinates; the plane of the galaxy is at 0 degrees latitude. Intensity gradations are color coded in the order black, blue, and red (highest). Note that the X-ray sources are concentrated in the plane of the galaxy. (Courtesy of Eli Boldt)

The source at the galactic center has attracted attention out of proportion to its intensity because it may provide evidence for the existence of a massive black hole in the nucleus in our galaxy. Infrared and radio observations suggest the presence there of a concentration of dark matter. The gamma ray observations made by the HEAO 3 Gamma Ray Spectrometer indicate that the galactic nucleus emits both a continuous spectrum of gamma rays and a bright, sharply defined line at the specific energy of 511 000 electron volts. The 511 000 electron volt line is exactly the energy of gamma rays produced when an electron and an anti-electron, or positron, interact and annihilate. Since positrons are quickly destroyed when they encounter electrons, the emission line must be produced quite near a source of positrons. Very high energy particles or electromagnetic fields are needed to produce positrons. A likely place to find such high energies is in the vicinity of a black hole.

This interpretation is supported by the observation that both the continuum and the line gamma ray brightness vary greatly over a period of about six months. This means that the source of the radiation can be no larger than the distance the gamma rays can travel in six months. Otherwise, time variations on opposite sides of the source would tend to cancel each other out, unless they were carefully coordinated, an unlikely situation. Since gamma rays travel at the speed of light, the gamma ray source must be less than about half a light year in diameter. This means that the source cannot be produced by a distribution of supernovas or other phenomena occurring in a cluster of stars, which typically has a diameter of several hundred light years. Thus we have yet another indication of a large concentration of matter and energy into a small region. A theoretical analysis suggests that the nucleus of our galaxy contains a black hole with a mass ranging from 100 to a million times that of the Sun.

In summary, an X-ray image of the Milky Way shows the following features: (1) bright sources associated with the young stars in the spiral arms of the galaxy; (2) bright sources associated with the old stars in globular clusters and the central bulge of the galaxy; (3) bright sources associated with the remnants of supernova explosions; (4) faint sources associated with degenerate dwarfs; (5) faint sources associated with normal stars; (6) a fairly bright source associated with the nucleus of the galaxy.

Before the launch of HEAO 2 (the Einstein X-ray Observatory), only three other normal galaxies had been detected in X-rays. For these three galaxies, the Large and Small Magellanic Clouds and the Andromeda Galaxy, we had no real X-ray images, so we could not know whether our galaxy was typical or not. Now over 50 normal galaxies have been imaged in X-rays, and the Magellanic Clouds and Andromeda have been studies in much more detail.

In general, these galaxies look much the way we would expect them to look, based on the picture that has emerged from the study of our galaxy. They have some bright sources associated with young stars and others associated with the older stars in the central bulges and globular clusters. The galaxies that are larger than the Milky Way have more bright sources, and the ones that are smaller have fewer bright sources than our galaxy. They also have sources that can be identified fairly confidently with the remnants of supernova explosions. The faint sources cannot be detected, but presumably they are there, too. Finally, most of the galaxies apparently have an X-ray source associated with the galactic nucleus.

Interesting anomalies exist, however. For example, at least half a dozen extremely bright sources have been detected in nearby galaxies. These sources are about 10 times brighter than the brightest galactic X-ray sources. They cannot be explained in terms of the conventional theory of accretion onto neutron stars. Therefore, either they represent new examples of black holes or an entirely new class of object, or we have overestimated the distance to these galaxies and hence the luminosity of the sources. Any of these possibilities has exciting implications. In the last case, it would mean that the distance scale to nearby galaxies would have to be revised downward. This would have far-reaching consequences, since our estimates of the size of the universe are based to a large extent on our knowledge of the distance to nearby galaxies, which serve as calibrators for measuring the much larger distances to distant galaxies and clusters of galaxies.

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Another interesting development has been the detection of excessive X-ray emission from "starburst" galaxies. These peculiar galaxies are apparently the sites of recent bursts of star formation. This follows from infrared, optical, and ultraviolet observations that show that the colors and spectral features of these galaxies are best explained by assuming that a large number of very young and massive stars are present. The reason for this activity is unknown. It could be that the close passage of another galaxy has created a shock wave, or dumped a large amount of gas into the starburst galaxy, precipitating the formation of new stars from a cloud of dust and gas. Or it could be that an explosion from the nucleus of the galaxy has shocked a gas cloud, causing stars to form.

X-ray observations provide a new approach to these issues, since both explosive nuclei and rapid star formation should be associated with enhanced X-ray emission. An X-ray survey of about three dozen of these peculiar galaxies shows that they typically are a few times brighter in X-rays than normal galaxies. In the cases that have been studied in detail, the excess X-ray emission can be attributed to an extended region around the

Visible light picture of the Andromeda Galaxy, the closest galaxy to Earth that is similar to the Milky Way Galaxy. (© Palomar Observatory)

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nucleus of the galaxy. The most likely explanation for this excess would appear to be that, since the galaxy has more massive young stars, it also has more of the high luminosity neutron star and black hole X-ray sources of the type that are associated with massive young stars. An analysis indicates that the burst of star formation would have had to occur less than about 10 million years ago. The sources appear to be concentrated near the nucleus of the galaxy. This would seem to indicate that violent activity in the nucleus has produced the burst of star formation and consequently the formation of bright X-ray sources. On the other hand, the correlation between nuclear activity and starburst activity is weak. It seems more likely that the stars form there because that is where the gas is. Many of the starburst galaxies are observed to have nearby companion galaxies, which suggests that a near collision between galaxies has precipitated the burst of star formation. Obviously there are more questions than answers to this problem for the present, and future observations covering the entire wavelength range will be needed before the conundrum of the starburst galaxies can be cracked.

Einstein Observatory X-ray image of the Andromeda Galaxy. Many bright X-ray sources are apparent. They are concentrated in the spiral arms of the galaxy and around the nucleus of the galaxy. (Courtesy of Leon Van Speybroeck)

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20
THE MAW OF THE ABYSS
Active Galactic Nuclei and Quasars

A persistent and universal symbol in the mythology of virtually every culture is that of a bottomless pit or an engulfing whirlpool. It was the maw of the abyss, and those venturing too close were dragged inward toward Chaos by an irresistible force. Socrates talked of a chasm that pierced the world straight through from side to side; Ulysses encountered it, as did a mythical Cherokee who escaped, but not before he was drawn down to the narrowest circle of the maelstrom where he could see into the nether world of the dead. And so it goes through Polynesian, Indian, Icelandic, Egyptian, and Sumerian mythology. Tradition is ambiguous as to the location of the whirlpool in the mythical landscape. Usually it was just beyond the boundaries of the known universe on the high seas, but some mythologies located it — properly, many astronomers would say — in the heavens, in Sagittarius in the Milky Way. That is, in the center of our galaxy.

In a sense, the search for a solution to one of astronomy's most persistent and perplexing riddles, the source of violent activity in galaxies and quasars, could be viewed as a continuation of the search for the whirlpool that is the maw of the abyss, a depth our telescopes cannot reach, and from which nothing returns. What is incredible to contemplate, and what sets us apart from the ancients, is that not only do we think we can locate engulfing maelstroms in the form of black holes in binary star systems and the nuclei of galaxies, we also think we have a fair idea as to how they are formed, how large they are, and so forth. A combination of theory and observation has led to the growing suspicion among many astrophysicists that the nucleus of virtually every galaxy harbors a massive black hole.

To an observer, the nucleus of a galaxy can be defined as a small region of high luminosity in the center of a galaxy. Optical photographs of most galaxies show such a bright center. The smallest size that can be detected is limited by atmospheric scattering to about half an arc second. This corresponds to a size of about 5 light years at the distance of the Andromeda Galaxy, about 100 light years for a galaxy at a distance of 50 million light years, and about 2000 light years for a galaxy a billion light years away.

Radio astronomers, using very long baseline interferometry (radio telescopes in West Virginia and California, for example, are phased together so that the ability to detect structure is roughly equivalent to a radio telescope 3000 miles across) have found galactic nuclear features 1000 times smaller than those detected with optical telescopes. These features

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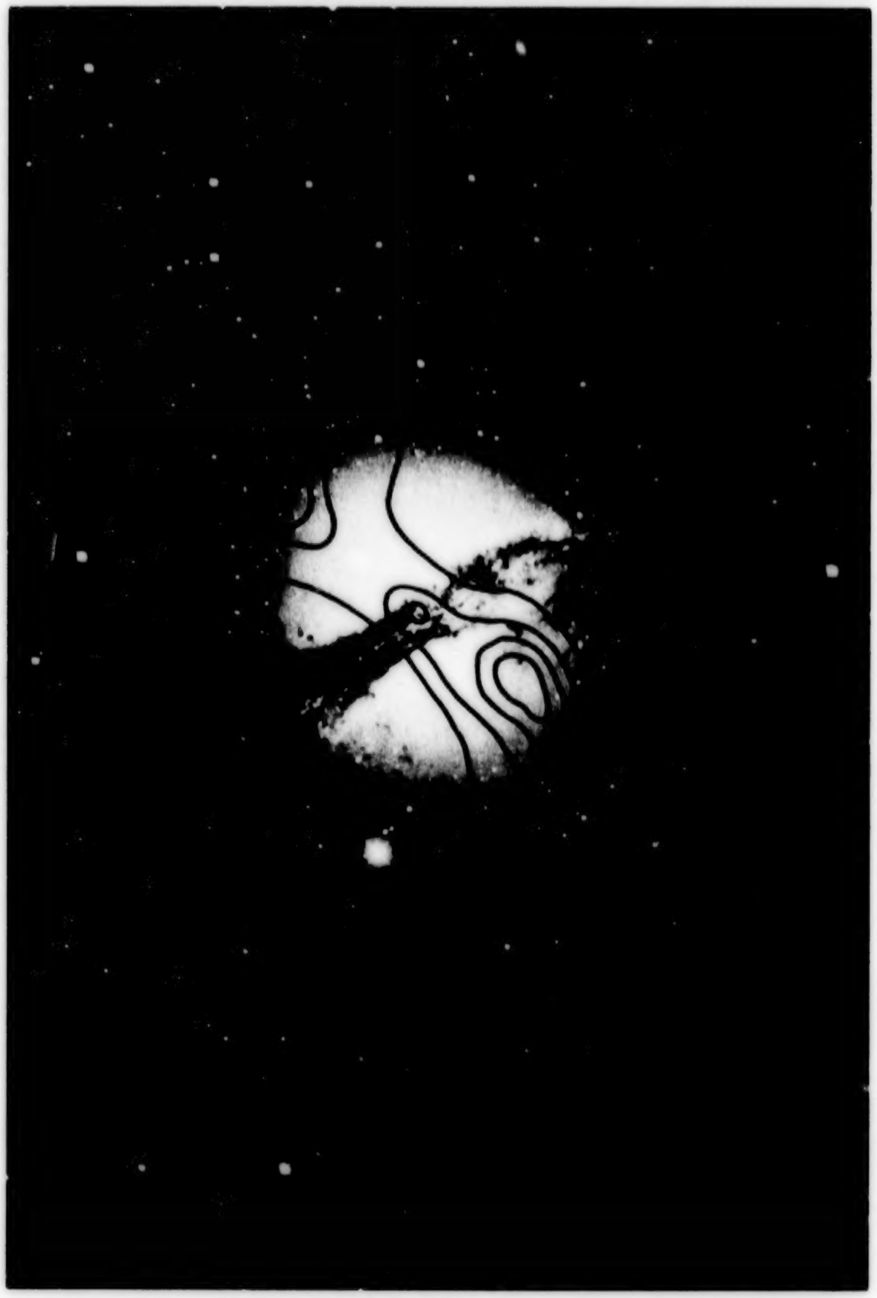

Visible light and radio images of NGC 5128. The intensity contours superimposed on the photograph of the galaxy NGC 5128 in the constellation Centaurus indicate that the nucleus of this galaxy is the site of violent activity. (Optical plate from Cerro Tololo Interamerican Observatory by John Graham; radio image by W. N. Christiansen, University of Sydney, Australia, © MNRAS)

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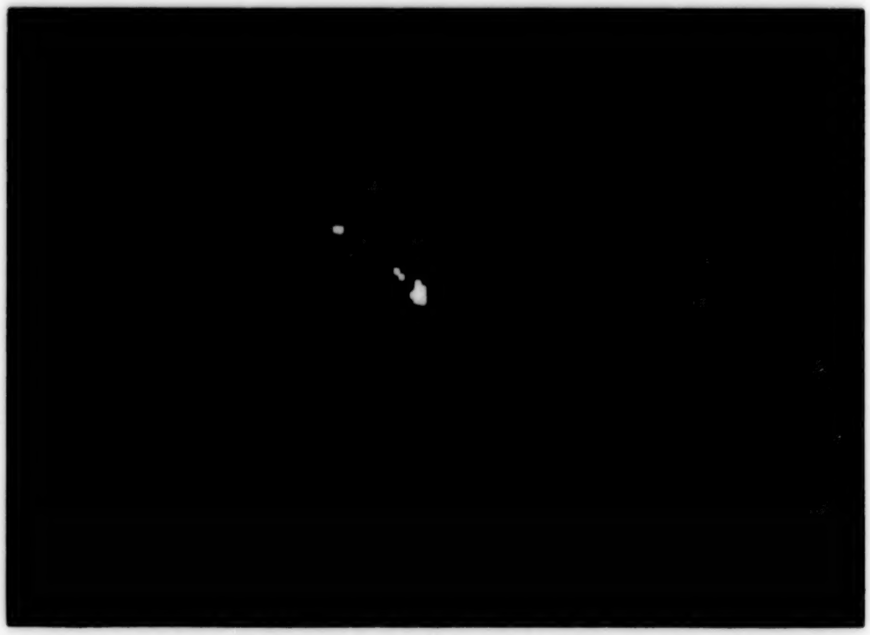
strongly suggest that the nuclei of galaxies are the sites of repetitive explosive activity in which clouds of high energy particles are ejected, always along the same axis of symmetry.

Over 50 of these jets have been observed and studied by the radio telescopes in New Mexico known as the Very Large Array. When these jets are large enough, they show up at optical and X-ray wavelengths. The HEAO 2 has detected X-ray jets in two violently active galaxies and one quasar. In each case, the jets extend out from the nucleus and point toward much larger bubbles, or lobes of high energy particles. The indications are that these objects, and presumably many others, have been undergoing explosive activity for a million years or more. The alignment of the jets of different size indicate that the explosive ejection of high energy particles has been channeled in the same direction, to a precision of a few percent, throughout the million years or so of violent activity.

There is further evidence of explosive activity. Large flares in radio, optical, and X-radiation are common in galactic nuclei and quasars. A gamma ray flare from the nucleus of our galaxy has also been observed (see Chapter 19). The flares occur at intervals ranging from years down to several hours. These variations can be used to set a limit on the size of the flaring region. Unless every particle in the region is heating up or cooling

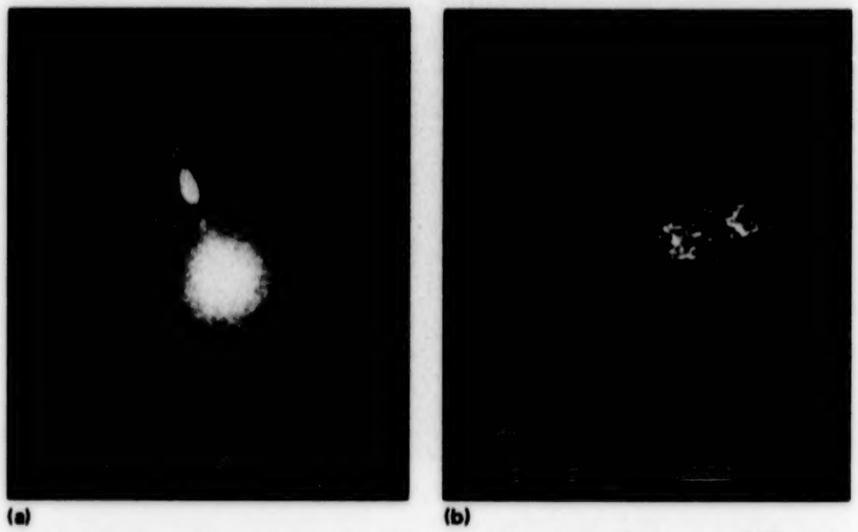


X-ray image, obtained from the Einstein Observatory, shows an X-ray jet extending from the center to the upper left, in line with the radio lobes. The jet indicates that energy in the form of high energy particles is continually pouring forth from the nucleus along a preferred axis. (Smithsonian Institution Photo No. 80-16249) down simultaneously, a very unlikely situation, or unless we are seeing some sort of reflection phenomenon, the stimulus for the variation must be able to travel across the nucleus in less than the observed time scale for the variation. In other words, the size of the flaring region cannot be so large that the time it takes a signal to travel across the region is longer than the observed time scale for the flaring. Otherwise, the variation would have been smeared out.

Since no signal can travel faster than the speed of light, it follows that a flaring source must have a size less than a light year if the flare occurred in a year, or a size of a light hour if the flare occurred on a time scale of an hour. This important result is central to the theory of quasars and galactic nuclei, because it limits the size of the source much more severely than do direct observations of the size. The HEAO X-ray observations have been most valuable in this regard. In half a dozen cases intense flaring has been observed on a scale of less than a day. This limits the size of the region to a light day, or roughly the size of our solar system. In three cases, the observed flares occur on a time scale of a thousand seconds or less. That means that, in the most extreme cases, an energy output of 10 billion suns is pouring forth from a region whose diameter is about that of Earth's orbit around the Sun! Conventional stellar energy generation processes, that is, thermonuclear reactions, will not suffice. We are driven to consider extreme conditions such as can be found in the vicinity of massive black holes.

One of the most important findings in astronomy over the past two decades is that violent activity is a widespread phenomenon that occurs in virtually every galactic nucleus. The HEAO observations have provided the latest and perhaps the most convincing evidence of this. Well over 100 galaxies have been detected as X-ray sources. They exhibit a continuous range of power generation in galactic nuclei, from normal galaxies such as our own and Andromeda, to quasars. It all suggests that the only difference between normal galaxies, the so-called active galaxies, and quasars, is the power level of the central source. A quasar seems to be an ordinary galaxy with an extraordinarily active powerhouse in its nucleus. What is the source of the violent activity in galactic nuclei and quasars? The observations indicate that two conditions must be met. In the words of astrophysicist James Gunn, an active galaxy must have a "monster" lurking in the nucleus and a supply of "food" for the monster. The monster is presumed to be a massive black hole that is fed by the infalling gas.

There are two basic reasons for the popularity of the black hole model for active galactic nuclei. First, there is observational evidence for the existence of dark massive compact objects in the nuclei of some galaxies. Second, plausible models involving the accretion of matter by a massive black hole appear to be capable of explaining many of the observed phenomena.

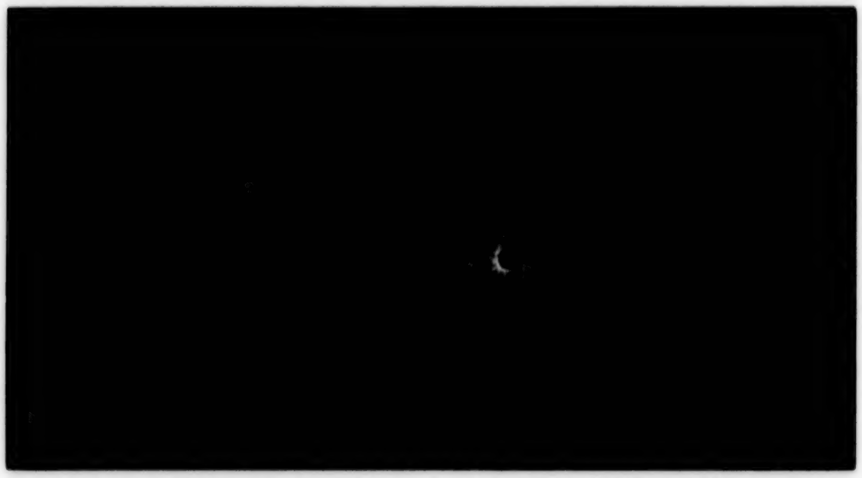


(a) (b)

Visible light (a) and X-ray images (b) of the jet in the center of the galaxy M87. As in the galaxy NGC 5128, the nucleus of the galaxy appears to have ejected a powerful beam of high energy particles and radiation (Optical image © Lick Observatory; Smithsonian Institution Photo No. 80-16248)

Infrared and radio observation of the nucleus of our galaxy indicate that a dark, nonstellar concentration of matter is needed to explain the motions of gas in the nucleus. The mass required is on the order of 5 million solar masses. The gamma ray observations from HEAO 3 provide further evidence. The observation of radiation from the annihilation of matter and antimatter seems to require conditions that are likely to be found only in the vicinity of a massive black hole (see Chapter 20). Observations of the nucleus of the Andromeda Galaxy imply a mass concentration of 10 to 100 million solar masses there. Optical observations of the nucleus of M87, a giant elliptical galaxy in the constellation of Virgo, show that the average velocity of stars in the nucleus rises rapidly inside the core. This is just the opposite of what would be expected if all the mass was in the form of stars. A nonstellar mass concentration in the nucleus of some 5 billion solar masses is needed to explain their results. The gravitational radius of such a black hole would be about the size of our solar system. This fits well with the time variations in the X-ray flux from a number of active galaxies, which require a power source of about this size or smaller.

None of these observations proves that there are black holes in the nuclei of galaxies. Other peculiar concentrations of mass, such as a superdense swarm of neutron stars and white dwarfs, or a single massive superstar, might work. But there is nothing to guarantee that these entities would not collapse to form a massive black hole. Indeed, it seems probable



X-ray image of the Quasar 3C 273, thought to be about 3 billion light years away. The source in the upper left is a previously undetected quasar, thought to be about 12 billion light years distant. (Einstein Observatory image, Smithsonian Institution Photo No. 80-16257)

that they would. The inevitability of gravitational collapse as the final state is a strong point in favor of black hole models — that and the cheap source of energy they provide.

At first sight, a black hole, the ultimate sink, would not appear to be a promising source of energy. The key to this paradox is the resistance of matter to compression. As the particles fall toward the black hole, they gain energy and crowd together. As a result, they radiate strongly in the ultraviolet, X-ray, or gamma ray band, depending on the size of the black hole and the conditions of the accretion. Under quite general conditions, the heating produced by accretion into a black hole can be 100 times as effective at producing radiation as the thermonuclear fusion reactions responsible for the energy generation in the Sun and most other stars.

Normally the gas would not be expected to fall straight into the black hole. Rather, it would spiral inward as part of a gaseous disk. If the radiation from the disk becomes too intense, it will exert a back pressure that prevents much of the matter from falling into the black hole. This effect, together with the buildup of magnetic stresses due to the twisting of the magnetic field in the gas, could lead to huge flares and the ejection of clouds of gas at very high velocities. The direction of the ejection would be along the rotational axis of the disk, that is, perpendicular to the plane of the disk. This provides a natural explanation for the observed ejection of matter from active galactic nuclei along a preferred direction.

HEAO observations of the spectrum and variability of the radiation from active galactic nuclei, in combination with observations at other wavelengths, can provide important checks on the theory sketched above

and allow us to study the physical state of matter near a massive black hole. Already the observations tell us that if a hot, churning, bubbling cloud of gas around a black hole is to explain the conditions in the center of our galaxy, then gas must be falling into the black hole at a rate of a few Earth masses per year. In the case of M87, the number would be more like several hundred Earth masses per year. In many active galactic nuclei, several thousand Earth masses per year would have to fall toward the black hole. For some of the most luminous quasars, roughly a million Earth masses, that is, the mass of a few solar type stars, would have to be accreted every year.

How are large black holes formed in the centers of galaxies? Nothing close to a consensus of opinion exists here, but one good possibility is that the formation of a central black hole naturally and inevitably results as globular star clusters spiral toward the center of the galaxy. Globular clusters are spherical clusters of a hundred thousand to a million stars. They are believed to be some of the first stellar units created during the initial formation of galaxies. These clusters, like individual stars, orbit the galactic nucleus in ponderous orbits that take millions of years. When they pass through the dense central regions of their parent galaxy, they suffer many grazing collisions with individual "field" stars. The cumulative effect of these collisions exerts a drag on the clusters, just as the atmosphere exerts a drag on satellites. As a result, the clusters spiral inward to the center of the galaxy until they are torn asunder by tidal forces.

In the course of billions of years, millions of stars may be concentrated into a region only a few light years across. These stars collide with one another, sometimes at high speeds, in which case they are partially or completely torn apart. Some of the collisions are gentle bumps, and the stars stick together, or coalesce. This new star presents a larger target, and more than likely it will eventually coalesce with other stars. The bigger the star gets, the more likely it is to be hit again and the faster it grows until it reaches instability, collapses on itself, and forms a black hole.

Once formed, a central "seed" black hole grows mainly through the accretion of gas accumulated in the nucleus. This gas could come from stars disrupted by collisions with other stars, from supernova explosions, from stars torn apart by the gravitational field of the black hole, or from gas falling into the galaxy from outside. In this connection it is intriguing that many active galaxies appear to have suffered a collision or near collision with another galaxy. Such encounters could result in the transfer of large amounts of gas from one galaxy to another, providing a plentiful supply of gas for the black hole.

When most of the stars and gas in the core of a galaxy have been swallowed up or ejected from the galaxy by the black hole, the nucleus of the galaxy settles down to a relatively quiet existence. This is probably the state of the nucleus of our galaxy. Every hundred million years or so it may flare up to a brightness 100 times its present level, when a globular cluster or especially large gas cloud spirals into the nucleus. These flaring episodes may correspond to what we are presently observing in some relatively nearby active galaxies.

This scenario explains the near universality of activity in galactic nuclei. It is all a variation on the same theme. Taken literally, it suggests that every normal galaxy was once a quasar, and every quasar will eventually become a normal galaxy. This is of course an over-simplification, but it may represent a rough approximation of the truth. This requires that the quasar phase be short lived on a cosmologic time scale, perhaps only a few million years. Exceptionally dense nuclei might produce exceptionally bright sources and exceptionally massive black holes, but normally, we might expect the quasar to shut off when the mass of the central black hole grew to a mass of several million suns. Normal galaxies are about 10 billion years old; if the quasar phase lasts only a few million years, or a few ten-thousandths of this time, then we would expect to see only a few ten-thousandths as many quasars as we do normal galaxies. This is about what is observed.

It would be foolhardy at this point to say that the enigma of quasars and active galactic nuclei has been solved. However, the progress in the last few years has been encouraging. The Space Telescope and advanced orbiting X-ray facilities planned for the 1980s should allow us to rule out alternative models, to find more dark, massive central cores in other galaxies, and hopefully to settle once and for all the age-old question as to the existence of an abyss in spacetime from which there is no return.

Until then, quoting Robert Frost,

"We dance round in a ring and suppose,
But the Secret sits in the middle and knows."

21

STRIPPED SPIRALS AND COSMIC CANNIBALS

Clusters of Galaxies

One of the primary goals of the HEAO project was to open wide the high energy window to the realm of the galaxies. This goal has been achieved. Galaxies of all sizes, shapes, and types have been detected. Some are relatively quiet, whereas others are exploding and ejecting jets of high energy particles that have been observed with radio, optical, and X-ray telescopes. Some galaxies evolve in isolation; others are found in clusters of galaxies, where they are constantly interacting with other galaxies in ways that profoundly affect their structure and evolution. Often they are stripped of the supply of gas needed to form new stars; sometimes they are gobbled up by other galaxies that are called, appropriately, cannibalistic galaxies.

Soon after it was realized that Andromeda and other spiral nebulae are galaxies of hundreds of billions of stars, it was recognized that galaxies are not distributed at random over the sky, but clump together in groups and clusters. About 10 percent of all galaxies are members of rich clusters of thousands of galaxies. One of the important discoveries of the high energy satellite experiments of the 1970s was that rich clusters of galaxies are pervaded by a tenuous gas that has been heated to temperatures up to 100 million degrees. The mass of this gas is comparable to that in the visible galaxies in the cluster, so X-ray observations have proven to be a sensitive method of detecting and studying such problems as the effect of the cluster environment on the member galaxies, the evolution of clusters as a whole, and the mass distribution in clusters.

Galaxies come in all sizes and shapes: majestic spirals, ruddy disks, elliptically shaped dwarfs and giants, and a menagerie of other more bizarre forms. Most currently popular theories suggest that conditions prior to birth — such as the mass of the protogalactic cloud, its size and rotation — largely determine whether a galaxy will be large or small, spiral and elliptical. However, when galaxies are crowded together, environment becomes more important than heredity.

The galaxies in the crowded central regions of rich clusters are constantly being pulled this way and that by the gravitational force fields of nearby galaxies. In addition, they are blasted and scoured by a hot wind created by their motion through the thin but pervasive hot gas in the cluster. These harsh conditions play havoc with a galaxy, so much havoc, in fact, that if our galaxy had happened to be in the central regions of a cluster rather than where it is, the Sun probably would never have formed.

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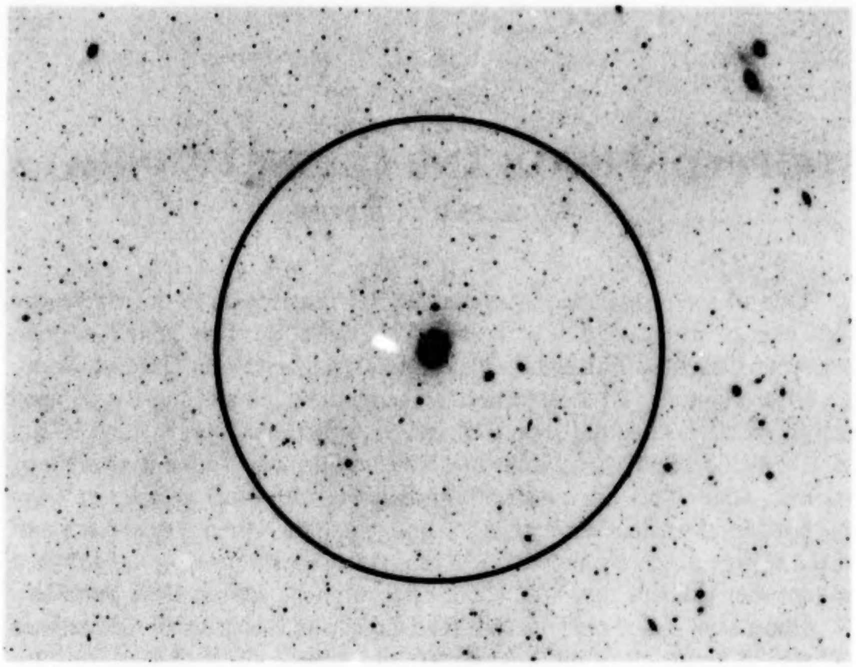


Cluster of galaxies in the constellation Virgo is typical of a large but irregular cluster containing more than 1000 individual galaxies. In this negative print of a photograph made with the 48-inch telescope on Mt. Palomar, the galaxies can be recognized by their fuzzy images. The large galaxy within the circle is the giant elliptical galaxy M87.

To understand this, let us take a closer look at the Virgo cluster. It is about 60 million light years away. Irregular in shape and covering about 100 square degrees in the sky (roughly the size of this book held at arm's length), the Virgo cluster contains at least 1000 spiral, elliptical, and disk-shaped galaxies. Its brightest members are giant elliptical galaxies, commonly identified by the numbers M84, M86, and M87, from the catalog of the French comet hunter Charles Messier (1730-1817). These colossal galaxies contain trillions of old stars, but few young stars, or clouds of gas such as the Orion Nebula in our galaxy.

On the other hand, the spiral galaxies on the outer edges of the Virgo cluster have bright, blue arms, indicating the presence of hot, young stars. Observations with radio telescopes indicate the presence of clouds of gas, too. In sharp contrast are the spiral galaxies nearer to the center of the cluster. They are redder in color, so they must have fewer new stars. They have less sharply defined arms and less gas. This trend continues into the core of the cluster, where spirals are rare. There we find mostly elliptical and disk-shaped galaxies. The latter resemble spirals that have had their arms ripped off. In fact, this is probably what has happened.

All galaxies are believed to have formed about 10 billion years ago. Why some of them became elliptical and some of them spiral is not well understood. It seems to have been related to the efficiency with which stars were born from the gas forming the galaxy and possibly to the rate at which the protogalactic cloud was rotating.

In elliptical galaxies the efficiency of the initial episode of star formation apparently was high, whereas in spirals the efficiency was lower and an appreciable amount of gas was left over to form a flat disk rotating around a central bulge of stars. Instabilities in this newly formed disk then generated a spiral wave pattern of hot, luminous, but short-lived stars. Over the course of 10 billion years, much of this gas has been used up by the formation of stars, first in the central regions and then over an increasingly large fraction of the disk. Eventually all the gas will be gone, and the bright spiral arms traced out by newly formed stars will gradually disappear. The central bulge will be the most prominent feature, and the galaxy will appear as a disk.

If star formation were the only means of using up the gas supply of a galaxy, a spiral galaxy should retain its pinwheel pattern for many billions of years. This is apparently the case for most galaxies. Approximately 50 percent of all the large galaxies in the universe are spirals. There simply has not been enough time for all the gas to condense into stars. Also, stellar winds and supernova explosions are recycling gas back into the interstellar medium to a certain extent.

However, in rich clusters such as Virgo, spiral galaxies are much less numerous; they amount to 30 percent or less of the total. Either they do not form as frequently in clusters or they age and disintegrate much more rapidly in the hurly burly of a rich cluster. Which is it?

X-ray observations using the HEAOs have helped to answer this question. They have shown that Virgo and other rich clusters are pervaded by a very hot low density gas. The density of this gas is highest in the center of the cluster and decreases smoothly toward the outer regions. In addition to this extended cloud of hot gas, pools of hot gas exist around the giant elliptical galaxies. These galaxies show up as bright spots on an X-ray map of the cluster.

The most massive galaxy in the cluster, M87, is located near the center of the cluster and is moving very slowly, if at all, through the intracluster gas. The X-ray source around it is caused by gas trapped in the gravitational field of this massive galaxy.

The galaxy M86, on the other hand, is moving rapidly through the cluster gas at a speed of several million miles an hour. The resulting aerodynamic drag heats and compresses the gas trapped around this galaxy, creating a brightening in X-rays. The aerodynamic drag, or ram pressure, is also stripping the gas from the galaxy as it moves through the core of the cluster. This shows up on the X-ray images as a plume of emission trailing behind the galaxy. An analogous process is the stripping of leaves from a tree in a windstorm. By the time M86 has crossed the central region of the core, it will have been almost completely purged of gas.

Consider now the fate of a spiral galaxy moving from the low density outer reaches of the cluster into the inner high density region. For 5 billion years or so it has been in a region where the aerodynamic pressure is low, and the process of star formation has proceeded unhindered. The spiral arms are clearly defined, and the galaxy has an ample supply of gas from which to form more new stars.

But once the spiral moves into the center of the cluster, the aerodynamic pressure, or wind, picks up and begins to blow the gas out of the galaxy. This occurs fairly quickly, after only a few hundred million years, during which time the galaxy has traveled only about a third of the way across the cluster core. This picture is confirmed by observations that show that virtually every rich cluster contains hot gas and that three-quarters of all spiral galaxies in the cores of clusters are excessively red due to the lack of new stars. Over a slightly longer period, the remnant spiral pattern dissipates; by the time the galaxy leaves the cluster core, it will have been transformed into a smooth disk galaxy.

If our galaxy had happened to form well within the core of a cluster such as Virgo, the Sun would probably never have formed. That is because

X-ray image of the central region of the Virgo cluster. This Einstein Observatory image shows the area around M87. The X-rays come from a halo of hot intergalactic gas that is trapped in the gravitational field of the galaxy. (Smithsonian Institution Photo No. 80-16250) the Sun is a second or third generation star located in the disk of the galaxy. It was formed from the leftover gas, 5 billion years or so after the initial period of star formation. In a rich cluster, the galaxy may well have been stripped of gas, and the Sun, or stars like it, might never have been formed.

As a galaxy moves through the core of a rich cluster, it not only encounters hot gas that scours it, it encounters other galaxies that can tear it apart. Collisions and close encounters with nearby galaxies can warp, stretch, and pull a galaxy apart, producing a weird zoo of strange forms. If the collision is a one-on-one affair at moderate to high speeds between galaxies of approximately the same size, they will emerge from the encounter distorted and a little ragged, but basically intact. However, if a galaxy coasts by a much larger one in a slow, grazing collision, it can be completely disrupted and assimilated by the larger galaxy. Under the right conditions these cosmic cannibals may consume 50 to 100 galaxies, bloating up in the process to become supergiant elliptical galaxies. These galaxies show up as bright optical and X-ray galaxies at the center of rich clusters.

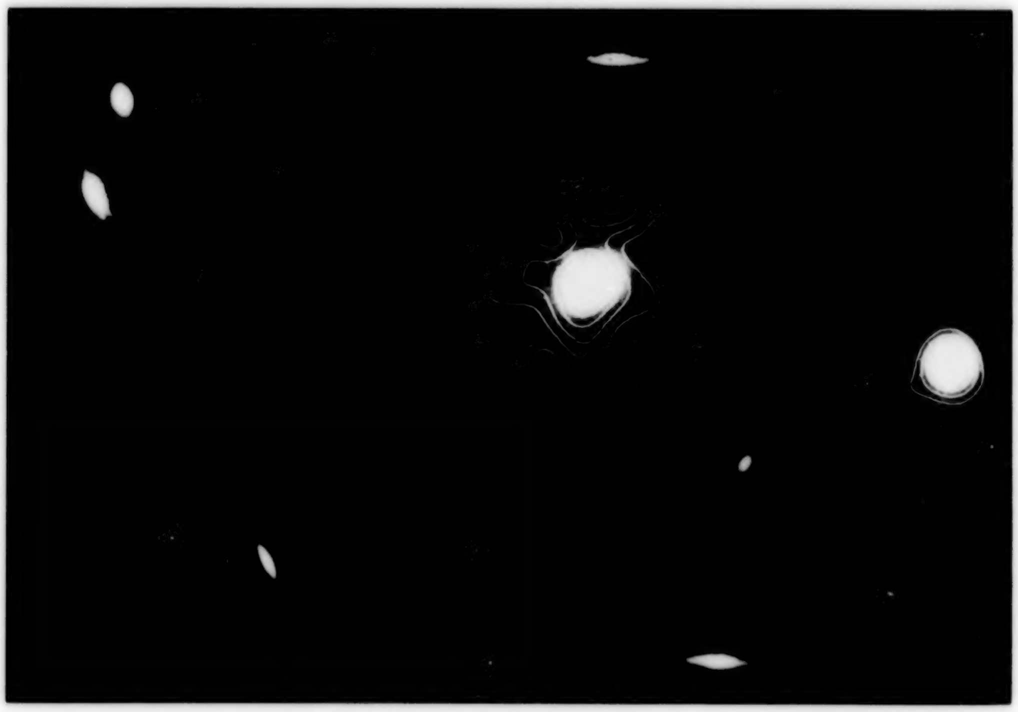
A cluster is a gigantic swarm of galaxies, in dynamic balance between gravitational energy and kinetic energy (the energy of motion of the galaxies). The collisions between galaxies in a cluster cause a gradual, inexorable tilting of this equilibrium in favor of gravity and a change of character of the cluster. Over the course of eons, the cluster, which may have started out with a loose irregular shape, will gradually become more compact and spherically shaped. X-ray images of clusters from HEAO 2 provide striking evidence for the different stages of this process. In effect, they give us snapshots of clusters at different stages of evolution. There are loose, irregular clusters that are dynamically young, and there are clusters that are best described as double clusters. These show two large clumps of gas and galaxies that have separately relaxed to smooth, quasi-spherical shape, but have yet to merge with each other. They are thought to represent an intermediate phase and to confirm theoretical ideas as to how clusters should evolve. Finally, there are clusters that show a smooth spherical shape, with the density of galaxies increasing toward the center.

In essence, galaxies in a cluster orbit around their center of mass in much the same way as planets and other solar system objects orbit around the Sun. In a rich cluster, the galaxies are so close together that some collisions inevitably occur. In most encounters, the galaxies do not meet head-on but are deflected only slightly as they brush past each other.

The cumulative effect of these collisions is to produce a dynamic friction on a large galaxy, slowing it down. As a result, it gradually spirals in toward the center of the cluster. Eventually, the gravitational forces that bind the stars to the infalling galaxy are overwhelmed by the combined gravity of the galaxies in the core of the cluster. Just as the ocean is pulled away from the shore at ebb tide by the Moon, the stars are pulled away from their infalling parent galaxy. If there is a large galaxy at the center of the cluster, it may ultimately capture these stars. With the passage of time, many galaxies will be torn asunder in the depths of this gravitational maelstrom and be swallowed up in the ever-expanding envelope of the central cannibal galaxy.

It takes a few hundred million years for a large galaxy to drift to the center of the cluster and to be cannibalized. This may seem like a long time, but in a few billion years, a central galaxy could have swallowed 100 or more galaxies! The association of X-ray emission with these supergiant galaxies is a natural consequence of the conditions in rich clusters. Because of the high concentration of galaxies, large amounts of gas are stripped from the galaxies. As this gas falls into the gravitational well around the supergiant galaxy, it becomes compressed and heated, producing a bright X-ray source. Around some supergiant galaxies, HEAO 2 X-ray observations indicate that this gas is cooling and falling onto the central galaxy. The eventual fate of this gas is unknown. Possibly it could go into forming new stars, or perhaps it could fuel explosive activity in the nucleus (see Chapters 19 and 20).

The contours of X-ray intensity measured from two galaxies in the Virgo cluster, M84 (right) and M86 (center), have been superimposed on an optical view of the same region. The swept back appearance of the contours for M86 indicate that hot gas is being swept out of this galaxy. (© National Geographic Society — Palomar Observatory Sky Survey)



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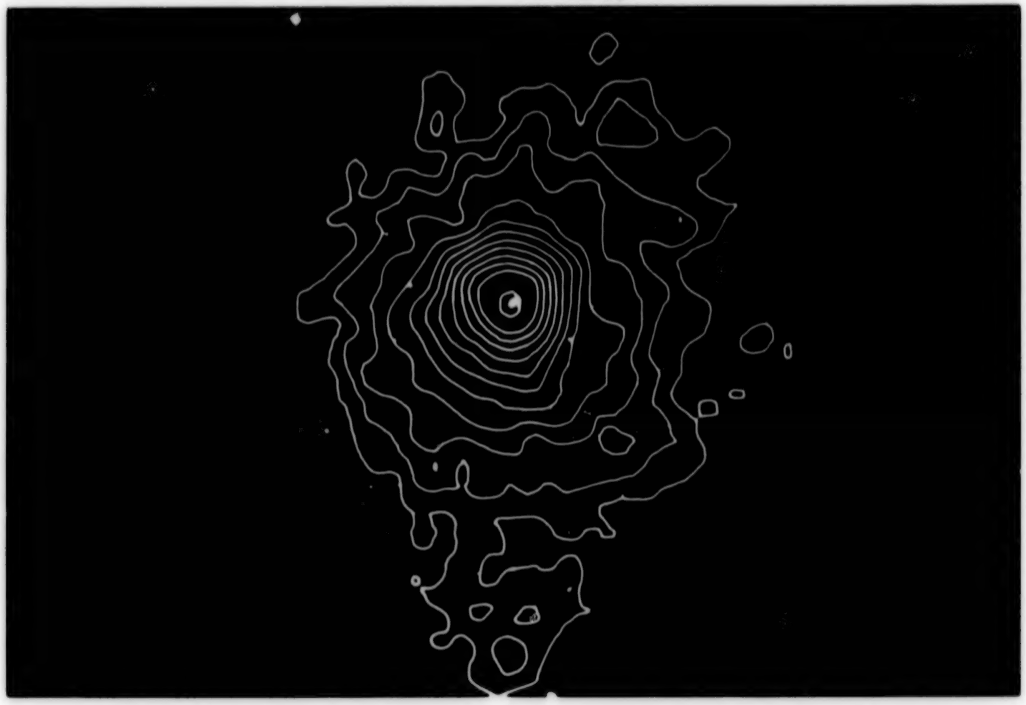


Cluster A85 with X-ray contours. X-ray intensity contours are superimposed on an optical photograph of the rich cluster of galaxies A85. The X-ray emission, which comes from hot gas trapped in the gravitational field of the cluster, is seen to be centered on bright supergiant galaxy. (Optical photograph © National Geographic Society — Palomar Observatory Sky Survey; Einstein Observatory overlays from Christine Jones; Smithsonian Institution Photo. No. 80-20241)

Galactic cannibalism also explains, in a natural way, another heretofore puzzling fact about rich clusters, namely, that there are very few, if any, bright galaxies in these clusters other than the central supergiant galaxy. That is, because the bright galaxies, which are the most massive, experience the greatest dynamical friction, they are the first to go down the gravitational well and be swallowed up by the central galaxy. Over the course of several billion years, 50 or so galaxies may have been swallowed up, leaving only the central supergiant and say, the fifty-first, fifty-second, etc., brightest galaxies. Of course, the process need not stop with 50 or 100 or 200 bright galaxies. Given time, all the massive galaxies in the cluster will be absorbed, leaving a rather sparse cluster composed of a supergiant galaxy surrounded by clouds of small dim galaxies, like a swarm of flies around the head of a dozing lion.

In a small, compact system of 50 to 100 galaxies, the evolution toward a cannibalistic supergiant galaxy will proceed 100 times faster than for clusters of 10 000 galaxies. We should be able, then, to find a system in which this transformation has already occurred. The small group of galaxies shown in the photograph on the preceding page is apparently just such a system. A central supergiant galaxy is surrounded by a few small galaxies. HEAO 1 X-ray observations imply that the central galaxy is enveloped by a cloud of hot gas containing as much mass as 10 large galaxies. The visible galaxies could not have supplied this mass. It must have come from galaxies that have long since been swallowed by the supergiant.

Returning closer to home, what about our Local Group of galaxies? Will our Milky Way Galaxy devour the small galaxies around us? Probably. Calculations indicate that the Large Magellanic Cloud should fall into our galaxy in a few billion years. When that happens, there will be few collisions among the stars of the two galaxies, but collisions between vast clouds of gas will be commonplace. Shock waves will rumble through the clouds, setting the heavens ablaze with candescent gas and triggering bursts of star formation. Some of these stars will rush through their evolution in a million years or less before exploding as supernovas. It will be a dazzling and perhaps a very dangerous time to be living in this galaxy.

22

THE MYSTERY OF THE MISSING MASS

Most of the mass in the universe is missing. Or is it merely hidden in some exotic, as yet undetectable form? No one is sure which. One thing is sure, though. The problem of the missing mass has gotten to the point where it is more than just a problem. It is an embarrassment, an obstacle to understanding such things as the structure of galaxies, the evolution of clusters of galaxies, and the ultimate fate of the universe.

A simple analogy illustrates the problem. Suppose the rockets inserting a spacecraft into an orbit around Earth were to burn too long, providing too much thrust. Then the gravitational pull of Earth would be overcome, and the spacecraft would shoot out of orbit into interplanetary space. Fortunately for astronauts, scientists can calculate quite accurately how much thrust is needed for a given orbit, so this does not happen. But suppose, through a computer error, the rockets burned too long and the spacecraft was accelerated to a speed twice as fast as the proper orbital speed – yet the spacecraft stayed in orbit! You would be forced to conclude that either Earth had more mass than you had supposed and hence a stronger gravitational pull, or that the theory you had used to make the calculation was in error.

This is about the situation astrophysicists find themselves in today. Not in trying to understand the motion of planets around the Sun – the theory works fine there – but in trying to understand the motions of stars and gas in the outer regions of galaxies, or of galaxies and gas in clusters of galaxies.

In the past few years astronomers have painstakingly measured the rate at which stars and gas clouds in the outer parts of spiral galaxies are orbiting the center of mass of those galaxies. Optical photographs show spiral galaxies to be graceful pinwheels of billions of stars, with the light falling off steadily from the central to the outer regions. Since the light is produced by stars, we naturally expect the matter and its associated gravitational force field to show a similar concentration. It follows, then, that the speed of rotation of the stars and gas should decline as one moves from the inner to the outer regions of galaxies.

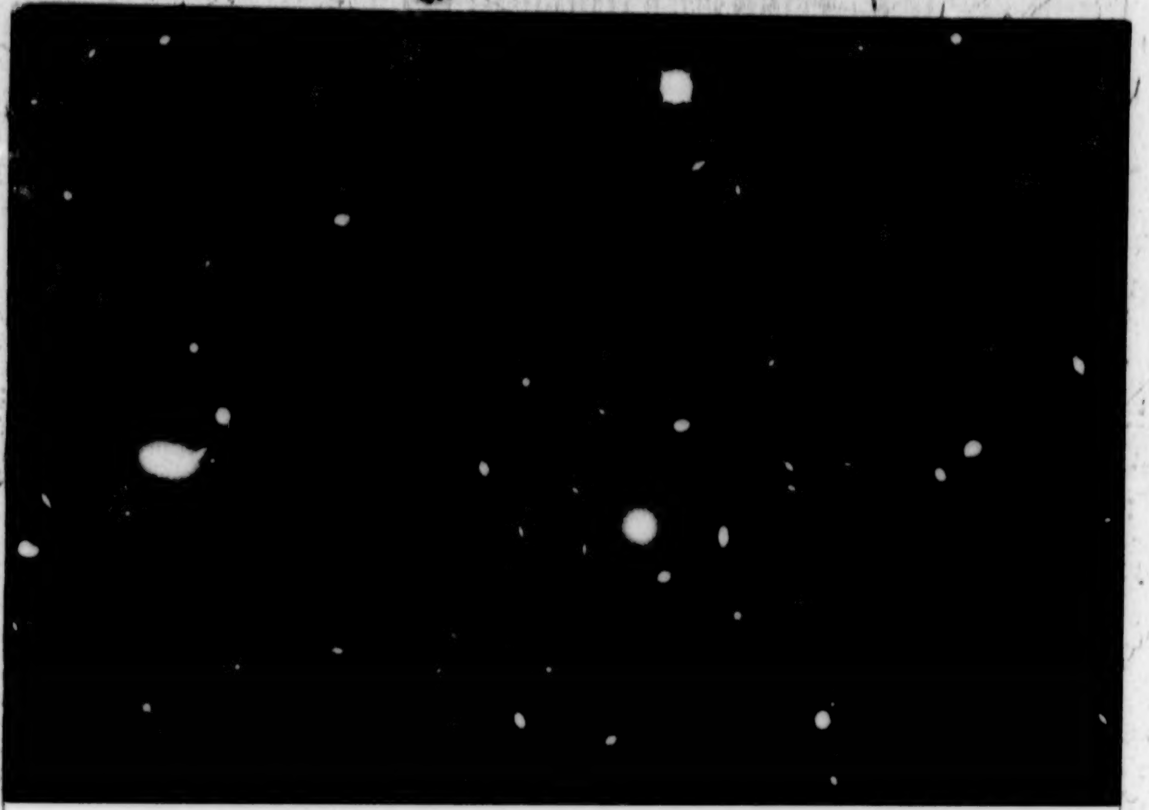
Much to the surprise and consternation of astronomers, this is not what is observed. As radio and optical observations have extended the velocity measurements for the stars and gas to the outer regions of spiral galaxies, they have found that the stars and gas clouds are moving at the same speed as the ones closer in! A substantial part of the mass of the galaxy is not concentrated toward the center of the galaxy but must be distributed in some dark, unseen halo surrounding the visible galaxy. The outer regions of galaxies, faint and inconspicuous on a photograph, may actually contain most of the matter. In the words of astronomers Margaret and Geoffrey Burbidge, it appears that "the tail wags the dog."

Just how large is this unseen halo? Why can't it be seen? No one knows the answer to either question. What is known is that the problem involves more than a few isolated galaxies. Most of the spiral galaxies in which the rotation pattern has been studied in detail, including our own Milky Way Galaxy, show evidence for an extensive halo of dark matter.

Nor is the problem confined to spiral galaxies. Perhaps the most spectacular evidence for a halo of dark matter around a galaxy comes from the giant spherically shaped galaxy, M87. X-ray observations show that M87 is enveloped in a cloud of hot, X-ray emitting gas nearly a million light years across. If this hot gas is not confined somehow, it will expand. In about 100 million years, it would disperse. Although this may seem like a long time, it is only 1 percent of the total lifetime of the galaxy. To account for the gas cloud as it is now observed, there are three possibilities: (1) some force is confining the gas to the galaxy; (2) the gas is being continuously replenished; or (3) we are observing the galaxy at a special time in its history, before the gas has had time to disperse. The third alternative is possible but improbable. The second not only requires an exorbitant amount of energy but also implies that the hot cloud should be spread out over a much larger volume of space than is observed. That leaves the first alternative, confinement by a force. The confining force could either be gravity or the pressure of an even hotter gas outside the M87 halo. Observations from the HEAOs rule out this latter possibility. That leaves gravity.

This is an important result. It means that X-ray observations can be used to measure the gravitational forces around galaxies. From the distribution of the X-ray brightness of the gas cloud, one can estimate the distribution of the gas in space. From that distribution, the mass needed for gravitational confinement can be estimated. Observations with HEAO 2 imply the presence of a halo of dark matter containing the mass of 30 trillion suns! This is several hundred times the mass observed in the disk of large spiral galaxies such as ours and the Andromeda Galaxy and about 30 times larger than the previous estimates of the mass of M87.

The same principles can be used to measure the gravitational field on a much larger scale. X-ray observations of clusters of galaxies show that the mass needed to confine the hot gas observed in clusters of galaxies is about 5 or 10 times greater than the mass that can be detected in these clusters through observation in any wavelength band, from radio through X-ray. This is in agreement with optical observations. They show that the motions of galaxies orbiting around the center of mass of the cluster can be understood only if the gravitational field is much stronger than would be deduced from the amount of detectable matter. That is, they imply that about 80 to 90 percent of the mass of the cluster has escaped detection.



Coma Cluster. This rich cluster of galaxies in the constellation Coma Berenices contains thousands of galaxies. Studies of the motions of the galaxies indicate that they are held together by their mutual gravitational attraction. The amount of mass present as visible matter, however, falls far short of the amount needed for gravitational stability. (Kitt Peak Observatory photo)

On an even larger scale, studies of the motion of the Local Group of galaxies that includes our Milky Way Galaxy indicate that we are part of a supercluster of galaxies. An analysis of the motion of the Local Group suggests that a large amount of hidden matter is necessary to provide the gravitational force needed to keep the supercluster from flying apart. The amount of missing mass is about 10 times the amount of visible mass.

In summary then, radio, optical, and X-ray observations of galaxies, clusters of galaxies, and superclusters of galaxies indicate that 80 to 90 percent of the matter is either missing or hidden from view. If this ratio holds throughout the universe, then our ideas as to the ultimate fate of the universe may be profoundly affected. In a large measure, the fate of the universe is determined by the mass density of the universe, that is, the amount of mass in a unit volume. If the mass density is larger than a certain critical value, the expansion of the universe that began with the initial "big bang" will not continue forever but will slow down, and the universe will collapse. The endpoint of such a collapse is unknown. The universe could collapse forever into a universe-sized black hole, or it could go through an unending cycle of expansion, collapse, and reexpansion. On the other hand, if the mass density is too low, the universe will expand forever; it will be "open." Current estimates indicate that the mass density of the universe falls short of the critical density by a factor of 10 or more, implying that the

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universe will expand forever. However, if the mass density is 10 times greater than it appears to be, as suggested by the missing mass mystery, then the universe may be closed after all. Seen in this light, the hidden mass problem becomes a very big problem indeed.

What is the answer to the problem? Is something wrong with our understanding of gravity? Is there some additional force that comes into play over these very large scales, a force that is missing from our calculations of the orbits or of the confinement of hot gas? Or is the universe full of dark matter that has escaped detection? Although attempts have been made to modify gravitational theory in the required way, most of the effort has been concentrated into ways that the matter could be hidden from view.

Astronomers have searched long and hard for this matter. They have used radio, infrared, optical, ultraviolet, and X-ray telescopes to scan the outer regions of galaxies and the intergalactic spaces for enough cool gas, hot gas, or dust. They have found some of each, but not enough to solve the problem of the missing mass.

A large population of white dwarfs, neutron stars, or black holes could remain hidden from the view of optical telescopes, but they would have to be 50 to 100 times more abundant on the outer edges of galaxies than in the regions of our galaxy that have been carefully observed so far. No plausible explanation as to why this should be has been advanced. Furthermore, if the population of collapsed stars were in fact 50 or more times larger in the outer regions, we might expect to find far more X-ray sources in the outer regions of galaxies than are observed. In addition, heavy elements ejected from these stars prior to their collapse should be 50 or more times more abundant in the outer regions of galaxies than in the inner regions. This is just the opposite of what is observed. Thus collapsed stars are unlikely candidates to explain the missing mass.

Another durable suggestion has been that a major part of the missing mass in galaxies and clusters of galaxies is made up of very low mass stars. These stars, which would have masses of only a few percent that of the Sun, are red, brown, and black dwarf stars. These stars are very dim because of their small size and low surface temperature. The red dwarfs, which have a mass of 10 to 50 percent that of the Sun, are known to be very common in the solar neighborhood. Of the 90 nearest stars to the Sun that have been classified, 62 of them are red dwarfs. Red dwarf stars produce intense radio, optical, and X-ray flares. This property should make it possible for advanced X-ray telescopes, working in concert with the Space Telescope, to attack the question as to whether 90 percent of the matter on the edges of galaxies is in the form of red dwarf stars.

Brown and black dwarfs are a much more difficult proposition. These objects, which are essentially freely wandering Jupiter-like objects, are so dim that it may be impossible to ever detect them. Although there are no sound theoretical reasons for believing that they exist in the required numbers, it is possible that such objects were produced in large numbers by the star formation process in globular clusters long ago, when galaxies were just beginning to form. The black and brown dwarfs may then have diffused out of their star clusters and formed very large halos around galaxies. Because of their low luminosities, they would be extremely difficult to detect, even if there were quadrillions of them around every galaxy.

One argument against the missing mass being in the form of normal matter of any type comes from cosmologic considerations. According to the big-bang model, the deuterium (heavy hydrogen) that is observed to exist in interstellar space was created about three minutes after the "beginning" in a billion degree broth of neutrons, protons, photons, and neutrinos. But if the broth were too thick, that is, if the mass density were too high, the deuterium would have all been processed into helium. The greater the mass density, the greater the fusion of deuterium nuclei into helium nuclei, and the less deuterium remains. By observing the amount of deuterium in interstellar space, we can get an idea as to the mass density of normal matter in the universe. The observations suggest that the mass density of normal matter is at most 10 percent of the value needed to turn around the present expansion.

This result lends support to yet another hypothesis for the missing mass, namely, that it is in the form of neutrinos. Neutrinos are elusive subatomic particles that are produced in certain nuclear reactions. Nuclear reactions of the type that produce neutrinos are thought to have been so common in the early universe that many cosmologists have believed for some time that we are literally awash in a sea of neutrinos.

Until recently, however, it did not seem to matter much, because neutrinos were thought to be particles with some energy but no mass, in the same way that photons have energy but no mass. Since it was thought that the energy of the neutrinos was by now quite low, the great abundance of neutrinos was of no practical consequence, or so it seemed.

Then a recent experiment suggested that the neutrino might have a very small mass. The mass of an individual neutrino might be very small, 100 million times smaller than that of a hydrogen atom. Yet, because there are so many neutrinos in the universe, their combined mass could dominate the universe! Thus, the solution to astronomy's greatest riddles, that of the missing mass, might have been found, not by studying distant galaxies, but in a series of experiments right here on Earth.

Serious questions about the neutrino hypothesis must still be answered. For one thing, further experiments have clouded the issue as to whether neutrinos really have mass, and if so how much. There is also a problem in understanding how it is possible for matter to form into galaxy-sized clumps in a universe dominated by fast-moving neutrinos. An analysis of this question suggests that clumps the size of superclusters would form first and that galaxies and clusters of galaxies would condense from these clumps. Yet the

HEAO observations of clusters of galaxies indicate that just the opposite happened. The neutrino hypothesis also suggests that the fraction of missing mass around galaxies should be much less than in clusters of galaxies. This is apparently not observed. These problems have led some astrophysicists to postulate that the existence of yet another particle, the gravitino, is responsible for the missing mass. Gravitinos would have been formed in the very early universe, less than about one millionth of a second after the expansion began, when the temperature was around 100 billion degrees. These particles, which are expected to be more massive than neutrinos, would condense into galaxy-sized clumps. The theory therefore predicts that the fraction of missing mass around galaxies is about the same as in clusters of galaxies. This is what the data now available suggest – a point in favor of the gravitino hypothesis. However, the data are sparse, and no one believes that the final answer is in. More data and calculations are needed.

Thus, the plot thickens, and the number of suspects multiplies in the mystery of the missing mass. And why not? That's the way a good mystery should read, and this is one of the best around.

23

COSMIC FIRE

The Cosmic X-ray Background

One of the driving forces behind astrophysical research is the practical justification that the universe provides us with a magnificent laboratory from which much can be learned that will be useful here on Earth. For example, we can get clues to the origin and nature of life or to new sources of energy, and we can find and study new states of matter and possibly new physical laws that govern the universe. Another, more philosophical, but equally compelling urge is our desire to comprehend the scheme of things. What is our place in this scheme? How did the universe begin, if indeed it had a beginning? Will it end, and, if so, when and how? These questions are the province of cosmology, the study of the universe as a whole: its large-scale structure, its origin, and its ultimate fate.

Since the beginning of X-ray astronomy, it has been apparent that X-ray observations would have an impact on cosmology. In 1962, the first X-ray sources outside our solar system were discovered as a result of a rocket flight that lasted about five minutes. The detectors on this rocket also discovered evidence for an apparently uniform background glow of X-radiation. This background is the reference level against which radiation from stars and galaxies must be observed. If we look at the night sky in visible light, we see a large number of bright spots plus a few diffuse patches of light on a black background. In the X-ray sky, the equivalent of the black night sky does not exist. We see a bright, diffuse emission that is the same in all directions. The uniformity of the background radiation means that it must originate far outside our galaxy. It brings to us information about the depths of space and time, if only we could decode it.

A variety of observations indicate that the universe as we know it began some 15 to 20 billion years ago in an explosion from a hot dense state. This is the big-bang theory for the origin of the universe. The high energy radiation produced when the universe was very young and very hot would have been absorbed and degraded as the universe expanded and cooled. The microwave background radiation first observed by A. Penzias and R. Wilson in 1968 is thought to be a relic of this very early state, when the universe was only about a million years old. The uniformity of microwave background indicates that the universe was homogeneous until it was a few million years old. Then, sometime between a few million and a few billion years after the start of the expansion of the universe, the universe made a transition from a uniform, featureless gas to the present state. In the present

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Deep X-ray survey in Eridanus. A survey with the Einstein Observatory of a region of the sky in the Eridanus constellation revealed three previously undetected X-ray sources that are associated with quasars. This and similar surveys suggest that the X-ray background radiation is produced by many very distant, unresolved sources. (Smithsonian Institution Photo No. 80-16256)

state, the matter in the universe is not uniformly distributed, but is in clumps of stars and galaxies. Why and how this transition from smoothness to clumpiness occurred is one of the great unanswered questions of modern cosmology. The X-ray background must have been produced sometime during this period, so studies of the background provide insight into this important phase of the universe.

Two theories currently vie to explain the X-ray background radiation. Both of them have support from the observations, and both have problems. Both cannot be right.

One theory for the origin of the X-ray background is that it comes from a 400 million degree gas spread throughout the space between the galaxies. The results of the HEAO 1 experiments show that the spectrum, that is, the distribution of the radiation according to wavelength, of the X-ray background matches very closely that expected from such a hot gas. Using the theory of how a hot gas radiates X-rays, the amount of intergalactic hot gas needed to explain the observed intensity of the X-ray background radiation can be computed. It is found that the total mass of this gas would be greater than all the matter in all the galaxies. This is not necessarily as unreasonable as it might sound. Some, and perhaps even a large fraction, of the gas that collapsed to form galaxies might have been left over in the form of a hot intergalactic gas. The density of the hot gas necessary to explain the X-ray background radiation would be very nearly that needed to close the universe, that is, to halt the present cosmic expansion and turn it into a collapse billions of years from now. In this event, the universe would be finite, and the universe as we know it would end in a cosmic fireball produced by the collapse.

There are serious problems with the hot gas theory for the X-ray background, however. The energy required to heat the gas to 400 million degrees would be enormous. Perhaps this energy could be derived from the collapse of matter to form galaxies, or perhaps some other means could be used to heat the gas, such as the energy given off by quasars and exploding galaxies. Furthermore, if the hot intergalactic gas exists, then it should evaporate all the gas trapped in clusters of galaxies. This obviously has not happened, since gas is observed in clusters of galaxies.

The other explanation for the X-ray background radiation is that it is caused by the superposition of many very distant individual sources, such as quasars. The X-ray telescope on HEAO 2 offered a way to decide between the two hypotheses, namely, a diffuse hot gas and distant individual sources. If the background is truly composed of a diffuse hot gas, then no matter how long an X-ray telescope looks at a particular region of the sky, the picture should not change. It should show a diffuse glow at all levels of sensitivity. Suppose, on the other hand, that the background radiation only appears to be smooth and is in reality composed of many individual sources. Then as fainter and fainter limiting fluxes of radiation are reached, more and more sources should appear.

That is what has happened. In two deep surveys of blank fields of the sky, that is, regions empty of known radio, optical, or X-ray sources, dozens of new sources have been found. About two-thirds of these sources are quasars. The surveys analyzed so far indicate that at least 30 percent of the X-ray background is due to individual sources such as quasars. It is known that there were more bright quasars in the past, about the time when galaxies were thought to be forming, so we should find more and more quasars as we look to greater distances, since we are in effect looking back further in time. Studies of the quasar population confirm this trend. This indicates that more than 50 percent and possibly all of the X-ray background could be due to quasars and other active galactic nuclei.

Can the observed spectrum, which is consistent with radiation from a hot gas, be explained in terms of radiation from distant quasars and active galaxies? In an effort to answer this and other questions, HEAO 1 investigators have taken the spectra of a large number of quasars and active galaxies. These spectra do not match the X-ray background spectrum. Either the quasars and active galaxies once radiated in such a way as to produce a different spectrum of X-radiation from what they are presently observed to produce, or they are not the source of the X-ray background.

In order to resolve the problems and contradictions, more information is necessary. Instruments even more sensitive than those used in the HEAO experiments will make it possible to distinguish between the alternatives, and we will be closer to understanding such fundamental questions as how and when did galaxies form? How did the universe begin? How will it end, if ever?

ADDITIONAL READING

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Astronomy, Mercury, Science News, Scientific American, and *Sky and Telescope.*

More technical reviews can be found in

Science, Nature, and *Annual Reviews of Astronomy and Astrophysics.*

For a striking visual presentation of some of the findings of the Einstein Observatory, see the "Visions of 'Einstein,' " a slide set of the X-ray images from the HEAO 2 satellite, produced by the Office of Printing and Photographic Services of the Smithsonian Institution in cooperation with the High Energy Astrophysics Division, Harvard-Smithsonian Center for Astrophysics, with an accompanying text by James Cornell and F. R. Harnden, Jr.

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Gerald D. Griffin	Deputy Director
Dr. Walter J. Kapryan	Director, Launch Operations
George F. Page	Launch Director, Expendable Vehicles
John Gossett	Chief, Centaur Operation Division
Laurence F. Kruse	Spacecraft Coordinator

Lewis Research Center

Dr. John McCarthy	Director
Larry Ross	Director, Launch Vehicles
Edwin T. Muckley	HEAO Project Engineer

Smithsonian Astrophysical Observatory

Dr. Herbert Gursky	Principal Scientist, Imaging Proportional Counter (B-4)

Dr. Harvey Tananbaum	Scientific Program Manager
Dr. Riccardo Giacconi	Principal Investigator, Monitor Proportional Counter (B-1) and High Resolution Imager (B-2)

Massachusetts Institute of Technology

Dr. George Clark	Principal Scientist, Focal Plane Crystal Spectrometer (B-3)

Columbia University

Dr. Robert Novick	Consortium member

Contractors

TRW Redondo Beach, Calif.	Spacecraft Design and Manufacture, Observatory Integration
American Science and Engineering Cambridge, Mass.	Design and Manufacture, X-ray Telescope System
General Dynamics Convair San Diego, Calif.	Launch Vehicle Manufacture

The HEAO 3 Team

NASA Headquarters

Dr. Thomas A. Mutch	Associate Administrator for Space Science
T. Bland Norris	Director, Astrophysics Programs
Richard E. Halpern	Manager, High Energy Payloads
Dr. Albert G. Opp	Chief, High Energy Astrophysics
John F. Yardley	Associate Administrator for Space Transportation Systems
F. R. Schmidt	Program Manager, Expendable Launch Vehicles

Dr. William Schneider	Associate Administrator for Space Tracking and Data Systems
Frederick B. Bryant	Manager, Space Tracking and Data Systems Network

Marshall Space Flight Center

Dr. William R. Lucas	Director
Dr. Fred A. Speer	Manager, HEAO Project
Fred S. Wojtalik	Chief Engineer, HEAO Project
Charles H. Meyers	Manager, Spacecraft Office
Joseph B. Jones	Manager, Experiment Office
Tom Irby	HEAO 3 Observatory Manager
Dr. Tom Parnell	HEAO 3 Project Scientist

Goddard Space Flight Center

Robert E. Smylie	Acting Director
Tecwyn Roberts	Director of Networks, Tracking and Data Acquisition
Albert G. Ferris	Director, Mission and Data Operations
Richard S. Costa	Mission Operations Systems Manager

Kennedy Space Center

Richard G. Smith	Director
Gerald D. Griffin	Deputy Director
George F. Page	Director, Shuttle Operations
I. A. Rigell	Acting Director, Cargo Operations
Charles D. Gay	Director, Deployable Payloads Operations
John D. Gossett	Chief, Centaur Operations
Larry Kruse	Spacecraft Coordinator

Lewis Research Center	
Dr. John McCarthy	Director
Larry Ross	Director, Launch Vehicles
Edwin T. Muckley	HEAO Project Engineer
Jet Propulsion Laboratory	
Dr. A. S. Jacobson	Principal Investigator, High Spectral Resolution Gamma Ray Spectrometer (C-1)
Center for Nuclear Studies, Saclay, France	
Dr. L. Koch-Miramond	Co-Principal Investigator, Isotopic Composition of Primary Cosmic Rays Experiment (C-2)
Danish Space Research Institute, Copenhagen, Denmark	
Dr. B. Peters	Co-Principal Investigator, C-2 Experiment
Washington University	
Professor M. Israel	Co-Principal Investigator, Heavy Nuclei Experiment (C-3)
California Institute of Technology	
Professor E. Stone	Co-Principal Investigator, C-3 Experiment
University of Minnesota	
Professor C. J. Waddington	Co-Principal Investigator, C-3 Experiment

Contractors

TRW Inc. Defense and Space Systems Group Redondo Beach, Calif.	Spacecraft Design and Manufacture, Observatory Integration
General Dynamics Corp. Convair Division San Diego, Calif.	Launch Vehicle Manufacture

Ball Corp. Technical Products Group Aerospace Systems Division Boulder, Colo.	C-1 and C-3 Experiment Design and Manufacture

ADDITIONAL PHOTO CREDIT

The pictures on the following pages are from the Smithsonian Institution slide set *Visions of 'Einstein'*: 35, 59, 60, 63, 66, 104, 105, 107, 109, 114, 115, 116, 140, 141, 144, 145, 147, 148, 154, 156, 157, and 166.

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ABOUT THE AUTHOR

Wallace H. Tucker is an astrophysicist who specializes in high energy astrophysics. Since 1976 he has divided his time between the High Energy Astrophysics Division of the Harvard-Smithsonian Center for Astrophysics and his home on the west coast, where he lectures at universities and writes. Dr. Tucker, a member of the American Astronomical Society, the International Astronomical Union, and the American Association for the Advancement of Science, received his Ph.D. in physics from the University of California, San Diego in 1966. He is author or coauthor of numerous articles in both scientific and non-technical publications.

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